Chapter 7

Analysis of Disturbances in the Power Electric System

The analysis performed in the previous chapters of this report is focused on normal operation and steady-state. Nevertheless, as any other installation, offshore wind farms must be protected against different eventualities.

For instance, when lightning hits the ground in the vicinity of a high-voltage transmission line or when lightning strikes a substation directly, the grid changes from one steady-state to another and a transient occurs. However, the majority of power system transients are the result of switching actions which are normally required for the ordinary operation of the electrical network.

Grid codes have specific requirements for voltage dips or faults at the PCC. So, these types of disturbances are well defined. Inside the offshore wind farm is also possible to appear disturbances, such as faults or disturbances related to breakers operation. Nevertheless, unlike for those ones at the PCC, for disturbances inside the wind farm are not specific requirements only protect the system. To this end, must be avoid instabilities and dangerous voltage / current peaks in the system.

Therefore, the normal operation analysis is not enough to carry out the pre-design of an offshore wind farms electric system. So, in the present chapter those disturbances and their associated transients are evaluated.

7.1 Transients in electric power systems

If a change in the normal conditions takes place in the power electric system, a temporary transient occurs. Consequently, due to the inherent dynamics of the electric system, the system needs a period of time to re-establish its previously steady-state condition.

A change in the normal conditions of the system can be programmed or accidental. If a lightning hits the ground close to a high-voltage transmission line or strikes directly a substation, the grid changes from one steady-state to another. As a result, this event will cause a transient.

Aside from lightning strikes, breaking actions also changes the system from one steady-state to another. Furthermore, the most of the power transients are caused by switching actions related to the breakers operation which, connects / disconnects parts of the network under load and no-load conditions [113].

The transients caused by breaking actions are related to the nature of the interrupted current. Thus, the transient after a disconnection during normal operation or after the clearing of a fault are considerably different. In this way, because of its magnitude and severity, short circuit current interruptions are especially of concern.

When a fault, in the form of a short circuit current, occurs in an electrical system and as a result of such fault, the part of the electric system where is localized the fault is disconnected. The protection device switches and interrupts the short-circuit current.

When a short-circuit current is interrupted, even at current zero as do the current interrupting devices, the magnetic energy stored in the leakage inductance of the transformer at the substation, in the inductance of the connection bus bars or in the submarine cables is still there.

Taking into account only a short period of time, it is possible to approximate a short-circuit current during a fault as a steady-state situation where the energy of the system is mainly stored in the magnetic field (high currents). So, when the fault current is interrupted, the system changes to another situation, where without current, the energy is predominantly in the electric field.

Between those situations, the magnetic energy stored in the mentioned components is transferred from the magnetic field to the electric field to adequate to the new scenario. As a result of this energy exchange a voltage oscillation appears in the system.

At a fault clearance, the fault and the disconnection (current interruption), both events are destabilizing changes to the system. The interruption itself produces an additional transient superimposed upon the instantaneous conditions of the system. Thus, interrupting devices must deal with transients in the currents generated elsewhere (for example due to a fault) and voltage transients caused by the interrupting device itself.

The voltage response at the instant of current interruption and the first few microseconds thereafter mainly depends on the lumped elements. After the first few microseconds, travelling waves have an important role in the transient recovery waveform.

The electromagnetic wave, which is caused by the interrupting device, propagates along a transmission line (constant characteristic impedance) with a fixed relation between the voltage and current waves. But if the wave arrives at a discontinuity, such as: an open circuit, a short circuit or a point where the characteristic impedance changes, an adjustment of the voltage and current waves must occur.

At the discontinuity, a part of the energy is let through and a part of the energy is reflected and travels back. In the case where the losses are neglected, the total amount of energy in the electromagnetic wave remains constant. Therefore, electromagnetic waves propagate through the system even after current interruption. Consequently, the resistive part of the circuit determines the losses of the electromagnetic wave and the duration of the oscillation caused by the switching device itself.

In this way, the accumulation of reflected electromagnetic waves with local oscillations gives the voltage waveform at the terminals of the interruption device. So, the shape of this waveform depends on the interrupted current, cable lengths, the propagation velocity of the electromagnetic waves, the reflection rates at the discontinuities of the system and the configuration of the power electric system.

In resonant scenarios with the potential to amplify some harmonics, the electromagnetic wave caused by the switching action can excite the resonant frequency of the system, which can causes additional over-voltages and instabilities to the system.

In short, switching operations and specially fault current interruptions have to be into account to avoid damages in the system caused by transient currents and voltages. Even more in systems such as the inter-turbine grid of the offshore wind farm with a resonant amplification potential. As a result a study of the transient is needed.

7.1.1 Fault clearance in the inter turbine grid

After the fault clearance, when a short circuit current is interrupted (even at zero current), a transient recovery voltage (TRV) will appear across the terminals of the interrupting device. The configuration of the network as seen from the terminals of the switching device determines amplitude, frequency, and shape of the current and voltage oscillations [114].

To determine the shape of the transient recovery voltage across the terminals of the circuit breaker, while clearing short circuits, many investigations are carried out. Thus, for different types of grids, a typical shape for the TRV is determined.

For large substations, like the considered offshore substation, if a fault occurs in one of the feeders, due to the number of adjacent feeders in parallel, the characteristic impedance seen by the circuit breaker is considerably smaller than the characteristic impedance of the faulted line. Therefore, for cases with the following network operation, Figure 7.1, the TRV exhibits the shape shown in Figure 7.2, [115] – [116].

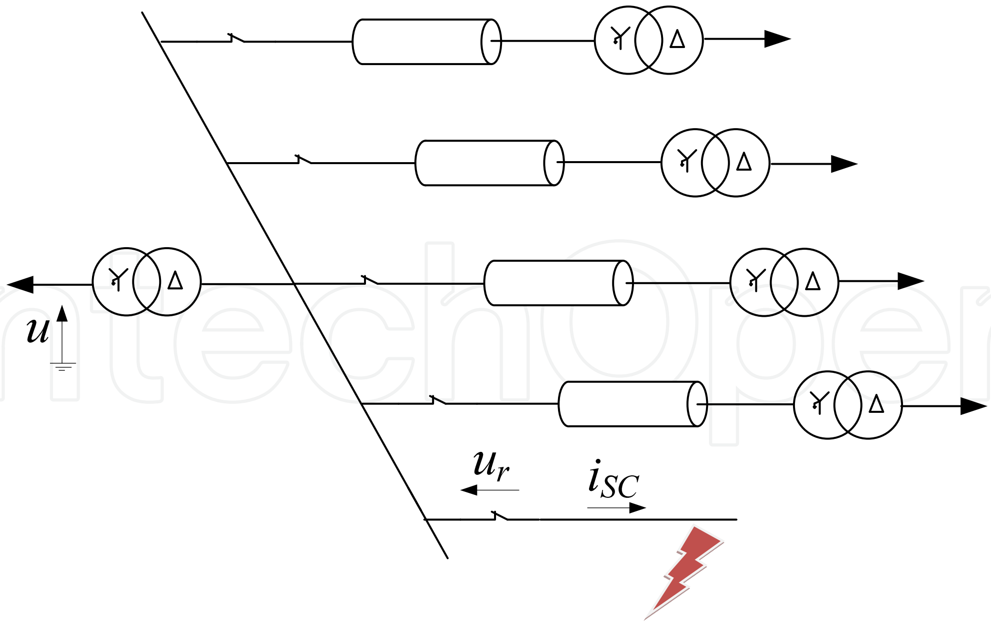


Figure 7.1 Generic large substation composed by several feeders.

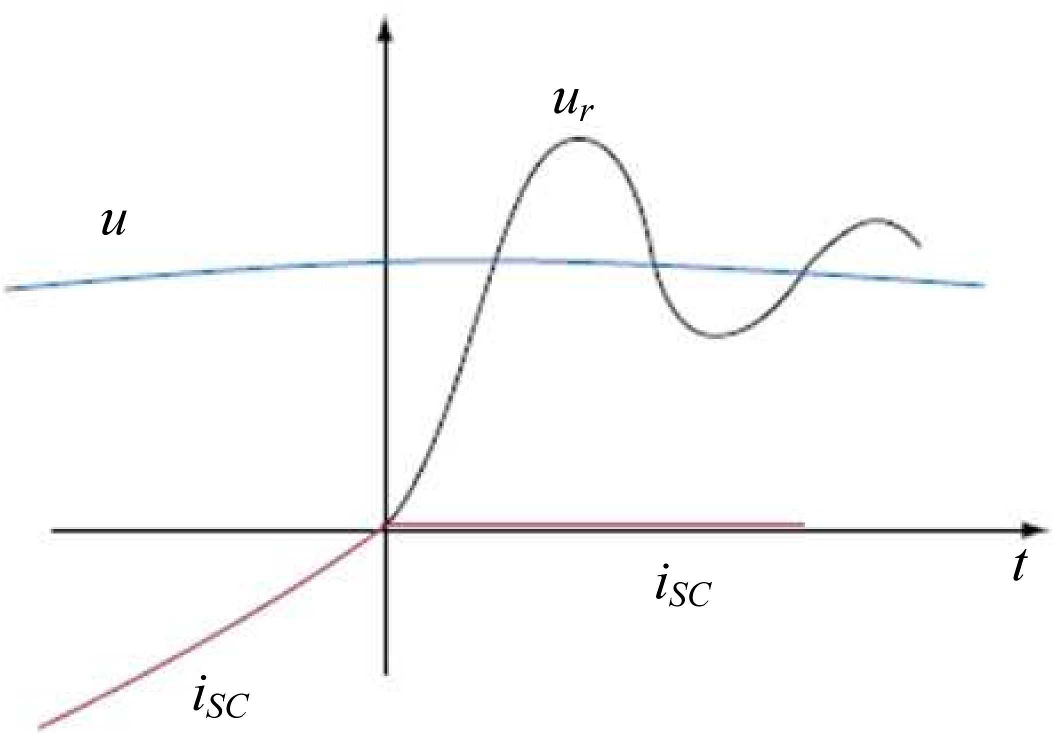


Figure 7.2 TRV for the considered network.

So, the considered inter-turbine grid for the base scenario has the potential to cause over voltages and oscillations at the clearance of a short circuit current in the inter-turbine grid.

7.1.2 Submarine cable energizing / de-energizing

Voltage and current transients can appear even earlier than faults, when a circuit is being energized or de-energized. In this way, the energizing / de-energizing transients of transformers, reactors, and submarine cables are especially of concern [117], [118].

The simple closing of a switch or of a circuit breaker to energize a circuit can produce significant over-voltages in an electric system. These over-voltages are due to the system adjusting itself to an emerging different configuration of components.

In the first step, a simply generic case is analyzed, a cable that is being energized through a transformer. For the sake of simplicity, a capacitor C is used to represent the transmission cable. The rest of the circuit is represented by an equivalent inductance and resistor. As a result of this simplification, the equivalent circuit can take the form of the circuit illustrated in Figure 7.3 (a second order equivalent circuit).

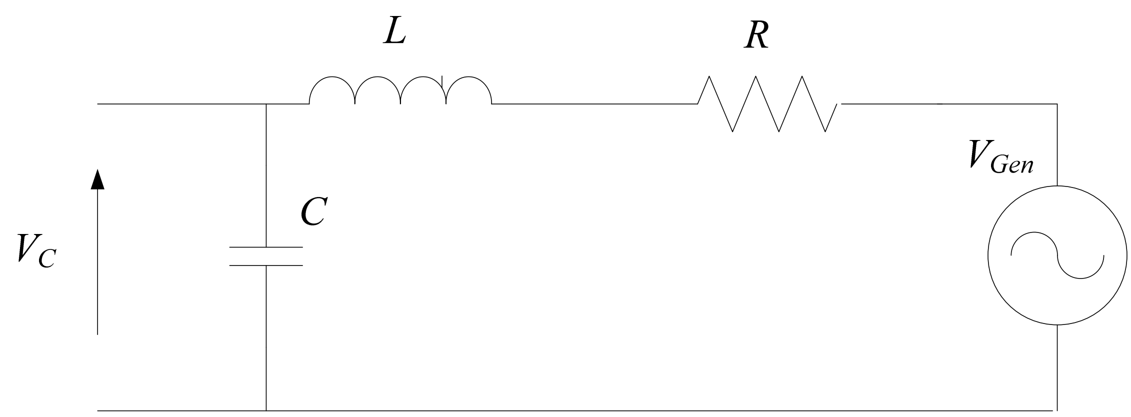


Figure 7.3 Single-phase RLC circuit.

Energizing a capacitive load is a well-known transient event, causing transient over voltages and inrush currents depending on the amplitude of the input voltage and the resistive part of the circuit. The equations in "s" domain that describe the behavior of the RLC circuit are:

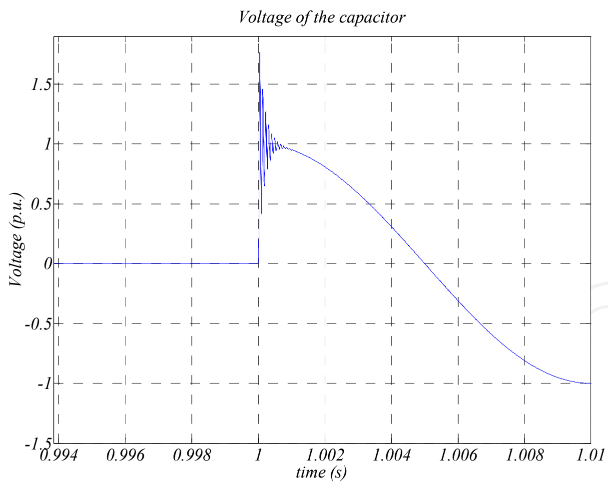
$$\frac{V_C(s)}{V_{Gen}(s)} = \frac{1}{LCs^2 + 2RCs + 1} = \frac{1/LC}{s^2 + Rs/L + 1/LC} \equiv \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{141}$$

$$2\xi\omega_n = \frac{R}{L} \tag{142}$$

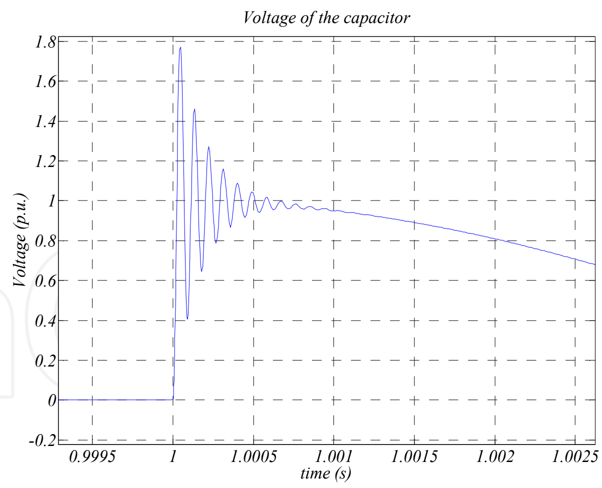
$$\omega_n^2 = \sqrt{1/LC} \tag{143}$$

As it can be seen in the equations (141) - (143), the transient response is determined in amplitude by the inductor combined with the resistive part. As regards to the oscillation frequency, is determined by the relation between the inductor and the capacitor.

The voltage on the capacitor during the energizing transient of the RLC circuit is depicted in Figure 7.4



(a)



(b)

Figure 7.4 Transient voltage of the capacitor during the energizing the RLC circuit, (a) Voltage on the capacitor and (b) voltage on the capacitor with more detail around the energizing.

The transient voltage, shown in Figure 7.4, oscillates along the line at a relatively low frequency (1/LC) for dumping factors lower than one ($\xi < 1$). It has an amplitude which can reaches a peak value approximately equal to twice the value of the system voltage that was present at the instant at which the closure of the circuit took place (if $\xi = 0$).

With regards to the current at the energizing / de-energizing, the series impedance limits the inrush current.

The case depicted in Figure 7.4, only shows the energizing of the capacitor, but the equations (141) - (143) also describes the behavior of the circuit during the de-energizing, because, these equations are calculated to describe the relation between the input voltage (V_{Gen}) and the voltage of the capacitor (V_C).

Applying a short circuit across the capacitor in this circuit is equivalent to applying a line to ground fault on a single-phase power system [117]. Thus, considering that the cable has a little resistive component ($\xi < 1$) and unless the cable energizing, a short circuit of 80% of depth. This simple circuit will behave as in Figure 7.5 [113], [115] and [117].

Note that the results illustrated at Figure 7.5 are a superposition of an AC voltage reduction (80%) and the transient depicted in Figure 7.4. The amplitude of the transient depends on the instant that the circuit breaker is closed (amplitude of the voltage variation) and the resistive part of the circuit.

With regards to the simplification of the system in lumped parameters, as is explained in chapter 4, section 4.2.2., it is possible to use of lumped parameters to represent a electric circuit, if the physical dimensions of the power system, or a part of it, are small compared with the wavelength of the voltage and current signals.

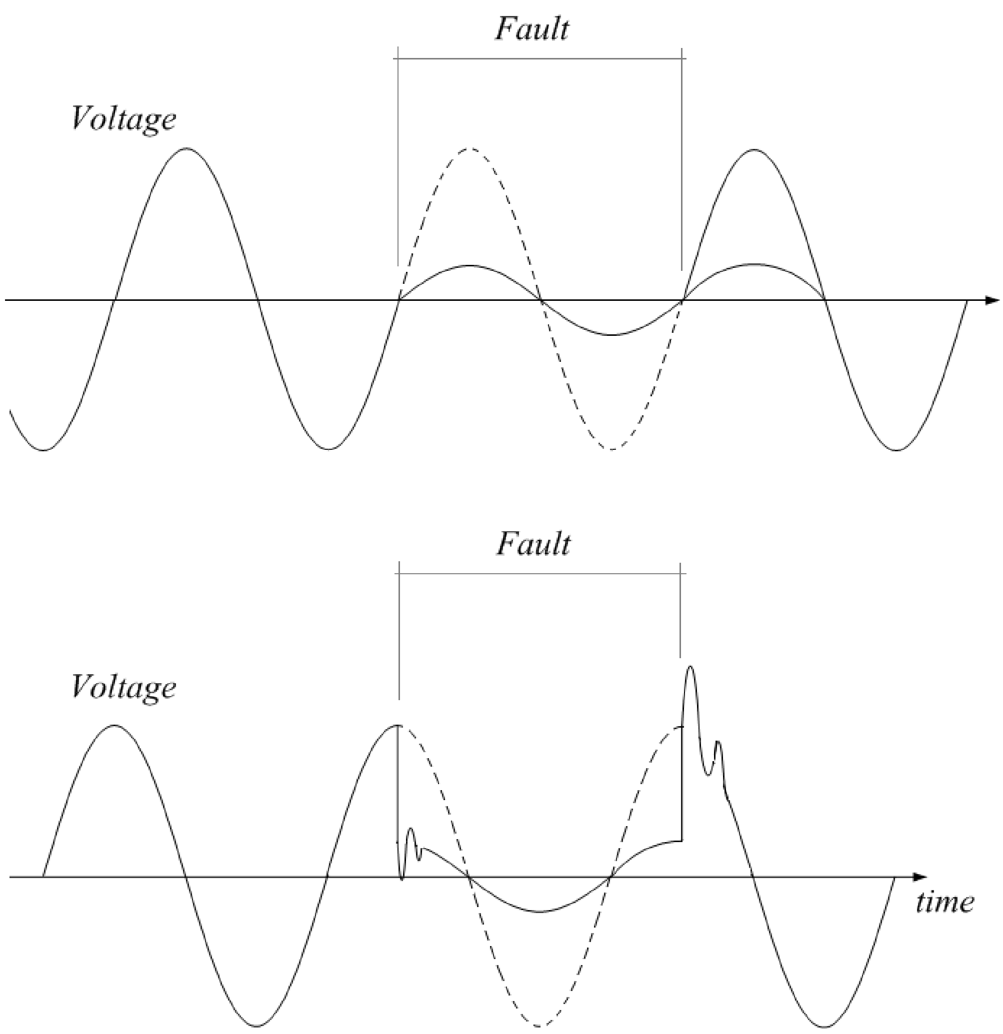


Figure 7.5 Voltage transients for a single phase RLC circuit, (a) the capacitor is short circuited at zero voltage and (b) the capacitor is short circuited at the maximum voltage.

Finally, to extrapolate the results of the single-phase system, a three-phase power system can be treated as a single-phase system when the loads, voltages, and currents are balanced.

The results of this simple system, considering a balanced three-phase voltage, are depicted in Figure 7.6.

One of the main differences between Figure 7.3 and the transmission system of the offshore wind farm is the inductive shunt compensators. As is explained and defined in chapter 4, the shunt reactors are used to improve the energy transfer capability of the submarine cable, reduce the active power losses, etc…

Therefore, the considered transmission system presents shunt (parallel) reactors at both ends of the line. As regards to how affects those reactors to the energizing of the submarine cable, [118] says that the shunt inductive compensator reduces over-voltages at the cable energizing. Thus, it recommends the connection of those reactors before the energizing of the cable to prevent over-voltages.

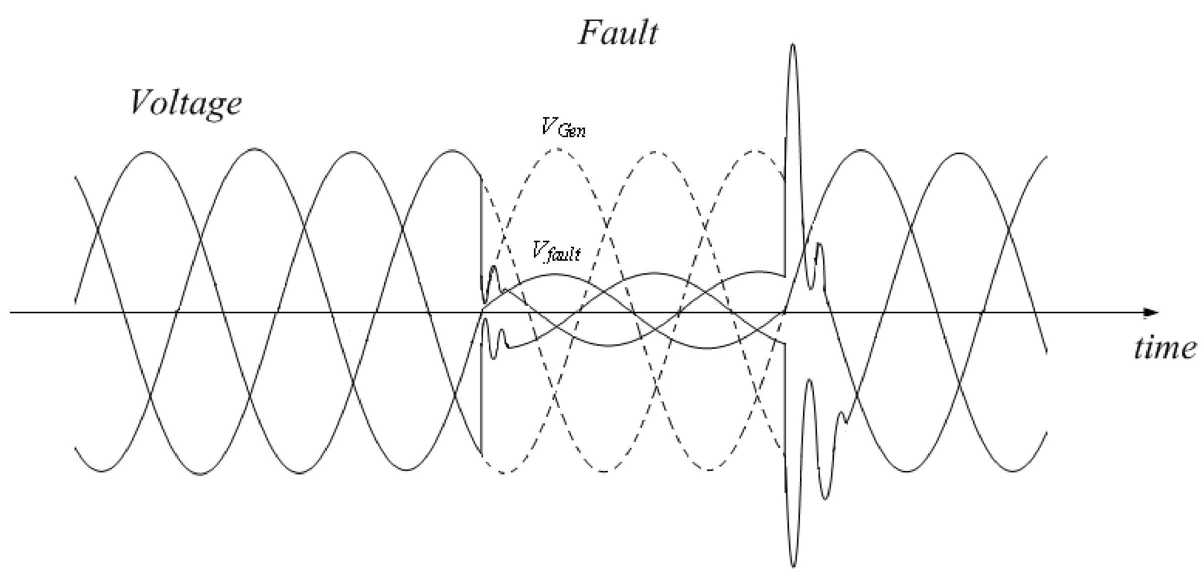


Figure 7.6 Voltage transients for a three phase fault balanced in a RLC circuit.

In short, the disturbances associated to the energizing / de-energizing of the submarine cables such as voltage dips at the PCC, have the potential to provoke over voltages and oscillations in the offshore wind farm.

Due to this fact, in the following sections, these disturbances which can cause instabilities and current / voltage peaks are evaluated upon the base scenario.

7.2 Considered scenario for the problem assessment

In order to perform grid studies, often complete models are not suitable because of the high computational effort required. Therefore, for such kind of analysis, usually reduced models are used [110], [119].

For this reason, in the present section, starting on the scenario with 30 complex wind turbine models described in chapter 5, an equivalent model is developed. As a result, the entire offshore wind farm can be simulated within acceptable time frames.

In contrast with the scenario of the previous chapter, this scenario is focused on evaluate the transient response of the electric connection infrastructure. Consequently, in the new simulation scenario, in order to model the behavior of the offshore wind farm, the main electronic aspects of the wind turbines are considered, like: the power electronic devices and their associated control strategies.

To this end, the scenario depicted in Figure 5.9, is simplified to another scenario with less computational cost. This simplification is carried out by using equivalent wind turbines instead of the complete feeders, i.e. the feeders composed by six wind turbines are substituted by an equivalent one. As claimed in [110] for instance, using N equivalent wind turbines it is possible to have reasonable accurate representation of an offshore wind farm made up with N radials. This simplification is validated in Appendix F: Comparison and validation of the equivalent feeder.

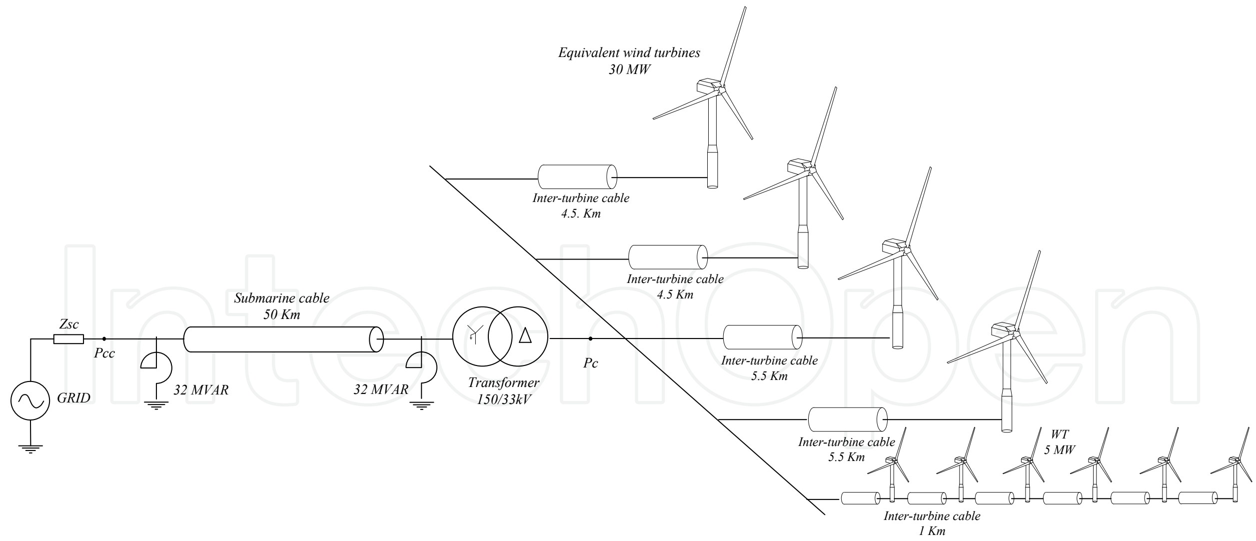


Figure 7.7 Considered scenario for the problem assessment.

Nevertheless, in order to analyze disconnection of wind turbines, one of the feeders of the wind farm is not simplified. Thus, the considered base scenario for the problem assessment is shown in Figure 7.7.

To simplify the real feeder (composed by six wind turbines, section 5.2.2) into an equivalent wind turbine, ideal voltage sources are used, i.e. the six converters of a feeder are simplified into a controlled voltage source.

Upon this voltage source an equivalent control is implemented to achieve the same behavior of the equivalent feeder and the full feeder. In other words, the ideal voltage source is provided with a control strategy with equivalent dynamics and behavior of the real feeder.

In the same way, the filter inductance is sized to keep the same dynamics and wave quality for the equivalent feeder and the full feeder, Figure 7.8.

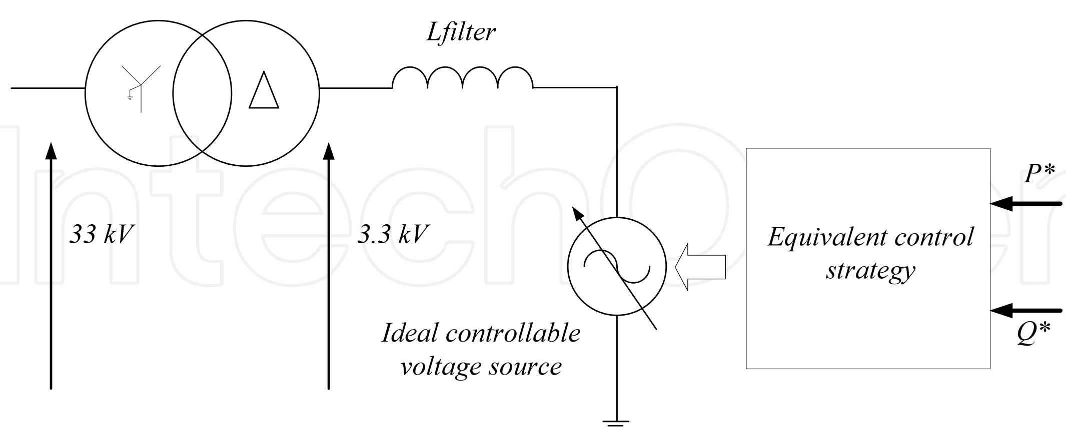


Figure 7.8 Control and power circuit of one phase of the equivalent wind turbine.

As regards to the inter turbine cables, those are simplified in an equivalent length. This equivalent length is calculated depending on the current though the inter turbine cable [120].

Through the cable segment used to connect the wind turbine Nº29 and wind turbine Nº30 only flows the energy generated in the wind turbine Nº 30 (Figure 6.13). Nevertheless, through the cable segment between the PC and the wind turbine Nº25 flows all the energy generated in the whole feeder. So, the equivalent length of the wind turbine cable is calculated as follows.

$$l_{equi} = \frac{6 \cdot S_{pc->25} + 5 \cdot S_{25->26} + 4 \cdot S_{26->27} + 3 \cdot S_{27->28} + 2 \cdot S_{28->29} + S_{29->30}}{6} \tag{144}$$

Where: l_{equi} is the equivalent inter-turbine cable length, and $S_{pc->25}$ is the cable segment length between the collector point and the wind turbine Nº 25 (1 Km) and $S_{NN->NN}$ inter turbine cable segments between wind turbines (1 Km).

7.3 Evaluation of breaker operations in the inter-turbine grid

A breaker operation can provoke instability on the system or voltage / current peaks as is discussed in section 7.1. Thus, in order to prevent problems associated to these actions. In the present section these kinds of operations are evaluated.

Based on the complete electrical scheme described in chapter 5 (Figure 5.25 in which are detailed the breakers and fuses), the points of the electric system where the wind turbine and feeder breaking operations are allowed are defined.

The protection system has breakers in each wind turbine after the step up transformer and for each feeder in the offshore platform.

As is mentioned in section 7.1, the power transients are caused by breaking actions under load and no-load conditions. Due to the fact that the transient caused by the breaking action are more severe depending of the magnitude of the interrupted current, only the most severe switching operations are evaluated: on-load switching operations. Therefore, in the present section three different cases are evaluated:

- The disconnection of one wind turbine from its breaker while this is operating at full-load (at zero crossing of the current).
- The disconnection of a feeder while this is operating at full-load (at zero crossing of the current)
- The disconnection of a faulted feeder (at zero crossing of the current).

As regards to the causes which can force those breaking operations, they can be several. For instance, the disconnection of a wind turbine can be forced due to a malfunction in the power electronics.

In the same way, if due to a fault, a short circuit current is circulating through one feeder, the faulted feeder must be disconnected, i.e. the breaker associated to this feeder (BRK 3 to BRK 7, Figure 5.25) has to interrupt the short circuit current.

7.3.1 On load breaker operations: Disconnection of wind turbines

The first of the considered switching action to analyze are the on-load wind turbine disconnections. In this way, if this disturbance causes instabilities in the system or unacceptable current or voltage peaks is evaluated.

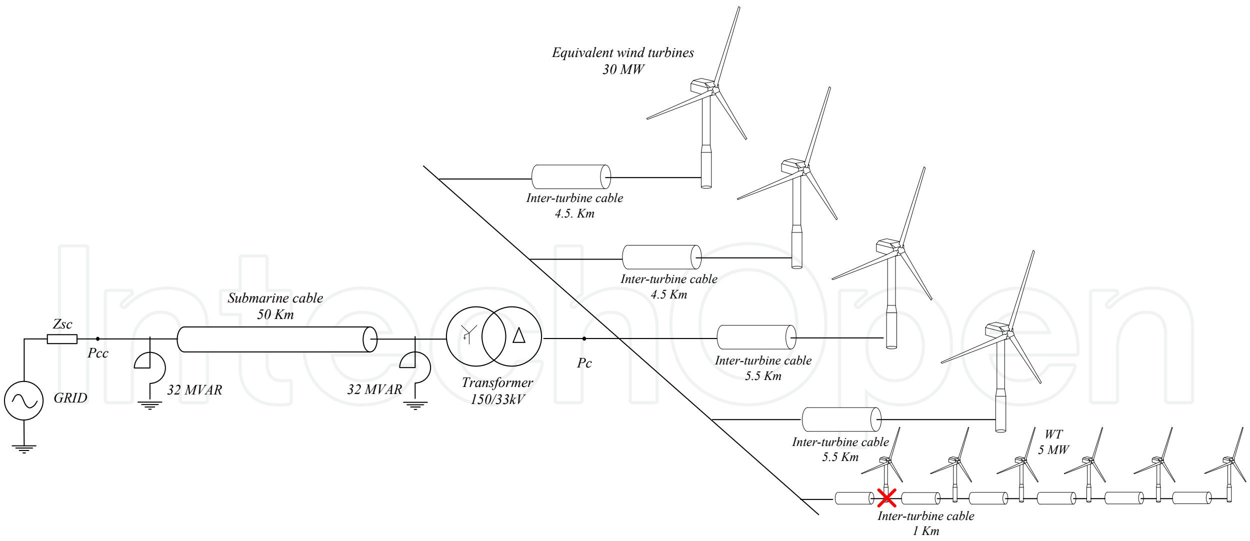


Figure 7.9 The scheme of the simulation scenario to evaluate the effect of the disconnection of a wind turbine.

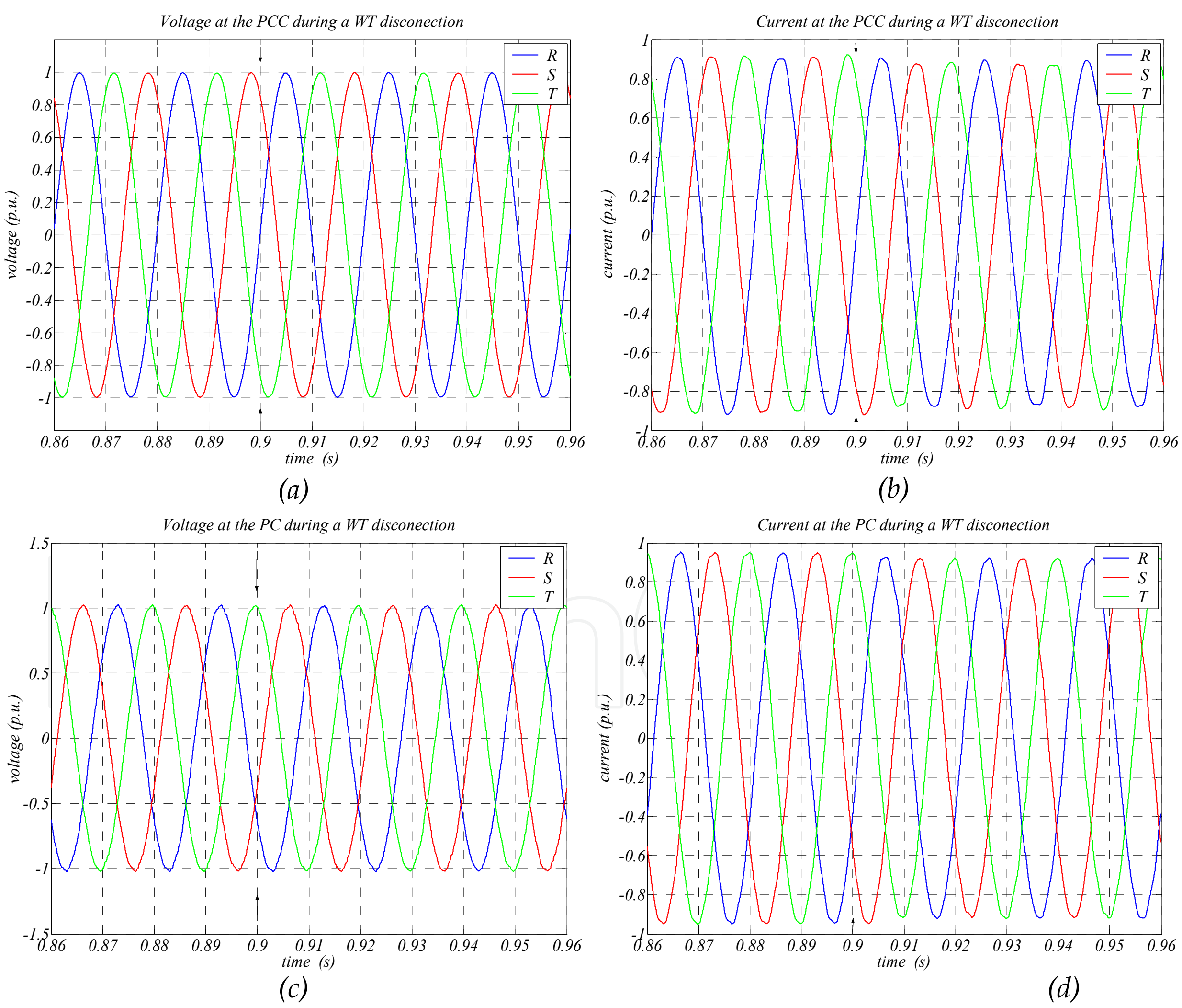


Figure 7.10 Three-phase signals (current and voltage) at the main points of the considered wind farm when the disconnection of a wind turbine occurs.

Thus, a disconnection of a wind turbine is simulated while this is generating the rated power. The simulation scheme is depicted in Figure 7.9 and the simulation results are shown at Figure 7.10. The disconnection order is given to the breaker at 0.9s (the breaker interrupts the current at zero crossing instant).

This disconnection does not cause a huge current reduction to the system. As a result, the transient does not cause any instability or peak problem at the collector point or at the point of common coupling. Furthermore, looking to the results illustrated in Figure 7.10, it is not possible to see any voltage or current oscillation caused by the disconnection.

7.3.2 On-load breaker operations: Disconnection of feeders

The second considered on-load switching operation is the disconnection of a feeder. As for the wind turbine disconnection, for the feeder disconnection also the wind farm and the disconnected feeder are generating the rated power. The disconnection order is given to the breaker at 0.9s and the breaker interrupts the current at zero crossing instant. The simulation scenario is shown in Figure 7.11 and the simulation results are depicted at Figure 7.12.

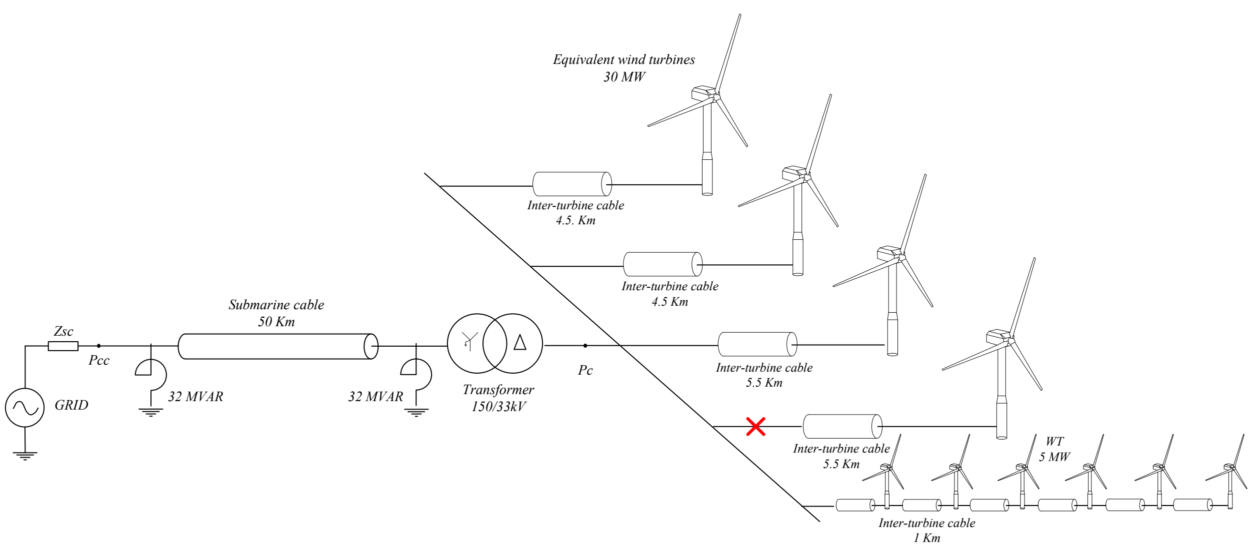


Figure 7.11 The scheme of the simulation scenario to evaluate the effect of the disconnection of a feeder.

The disconnection of a feeder does not cause a significant current reduction to the system, thus, the transient caused by the circuit open does not provoke any instability or peak problem at the collector point or at the point of common coupling. Nevertheless, it is possible to observe a signal oscillation at the PC, Figure 7.12*(c)*.

The protection breaker to disconnect a feeder is suited in the offshore substation, which means that if the feeder is disconnected, the resultant electric scheme is different in comparison with the scenario before the disconnection. It changes the capacitive component so the oscillation frequency does too (see chapter 6, section 6.5.2).

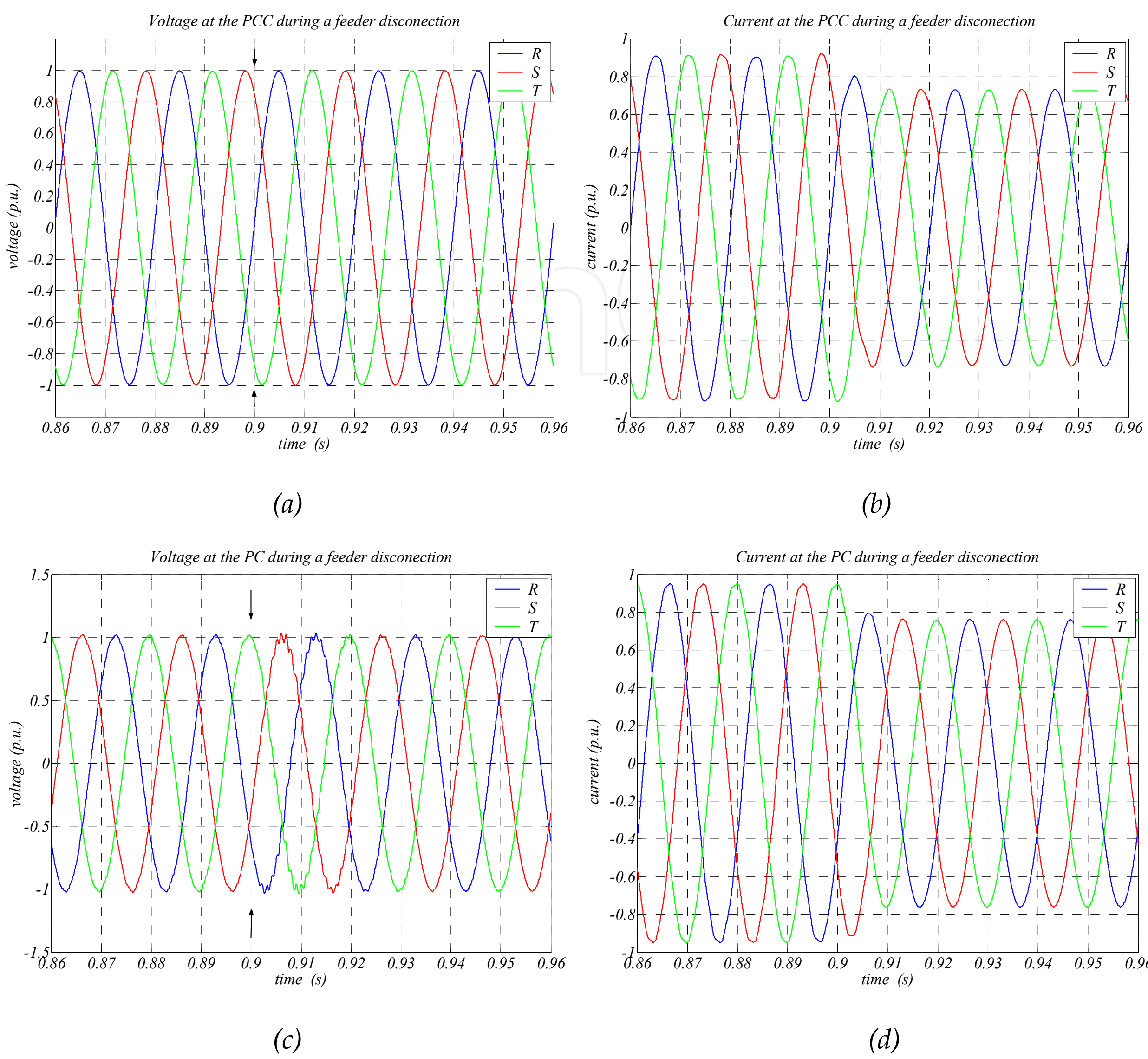


Figure 7.12 Three-phase signals (current and voltage) at the main points of the considered wind farm when the disconnection of a feeder occurs.

7.3.3 On-load breaker operations: Fault clearance in the inter-turbine grid

For the last case, the disconnection of a feeder at zero current during a fault (phase to phase) is simulated. A fault causes a short circuit current through the feeder associated to BRK7. So, to protect the integrity of the system, after 60ms (0.9s) of short circuit (the delay time considered to operate the breaker), the breaker interrupts the current at zero crossing instant. The simulation scenario is shown in Figure 7.13.

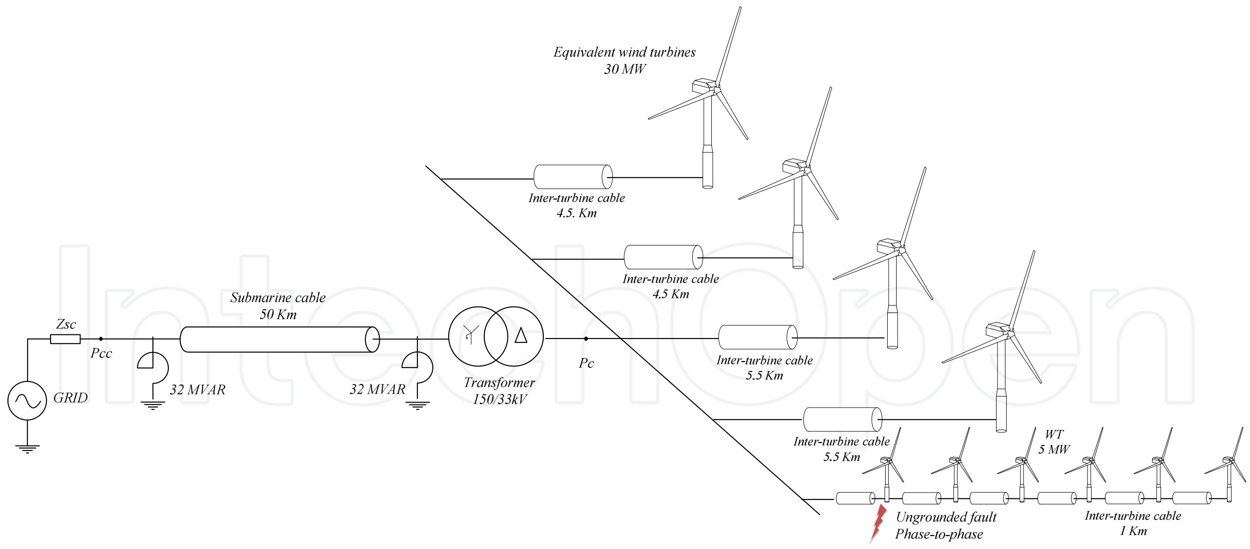


Figure 7.13 The scheme of the simulation scenario used to evaluate the effect of the disconnection of a feeder during a short circuit fault (phase to phase).

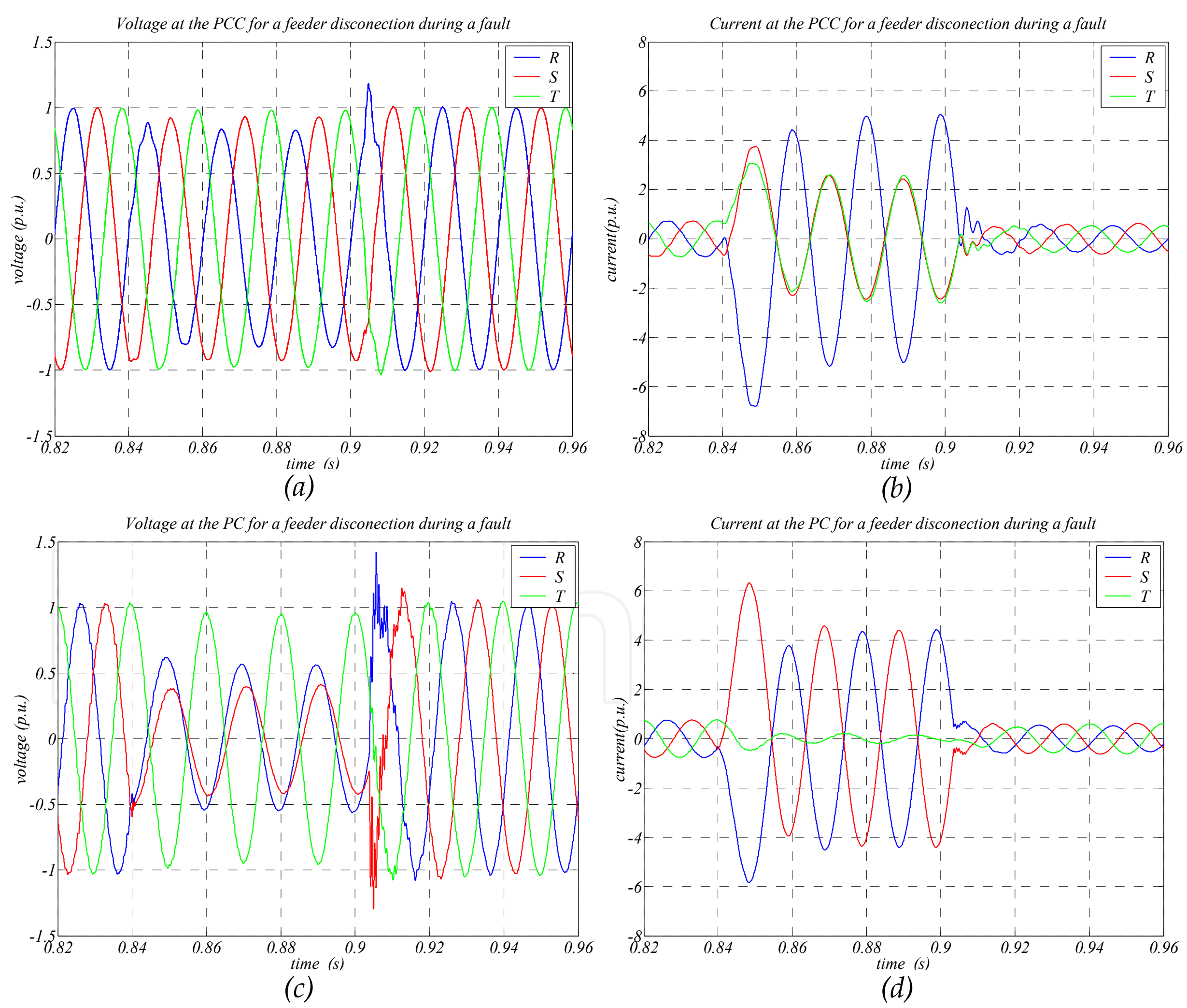


Figure 7.14 Three-phase signals (current and voltage) at the main points of the considered wind farm when a feeder is disconnected during a short circuit fault.

In the results depicted in Figure 7.14, it can be observed that the short circuit current is given mainly by the main grid, due to the fact that the wind turbines have a current limit and they cannot inject infinite current. This causes an unbalanced transient in the PCC, but this transient has a short duration (60ms) and does not causes instabilities to the system.

Looking at Figure 7.14 (c), there is a voltage peak at the PC with a transient oscillation (naturally dumped). The voltage peak has the amplitude close to the 50% over the nominal voltage. As regards to the frequency of the transient oscillation, this frequency is 1200 Hz, the natural frequency of the system.

These voltage oscillations with a peak value of 50% of the nominal voltage, can damage the power electronic devices of the system. However, the voltage and current peaks measured in simulation are not dangerous for the main elements of the transmission system: Step-up transformer, submarine cable and inductive compensators. Although, according to some studies, high frequency transients (not only peak value) are apparently the responsible of insulation failures in transformers [121].

In this way, in Middelgrunden and Horns rev wind farms almost all the transformers had to be replaced with new ones due to insulation failures [122] and in [123] it is suspected that the fast switching breakers caused the insulation failures in these transformers.

Nevertheless, the direct proof of the negative impact of the high frequency transients on the transformer insulation is not yet found [124].

Over-voltages in transmission and distribution systems cannot be totally avoided; however, their effects can be minimized, i.e. the magnitude of the over-voltage can be limited by the use of appropriate elements.

Nevertheless, the objective of this book is the better knowledge of the nature of those transient over voltages and currents, i.e. identify the possible problematic aspects. So, the mitigation of the voltage peaks by using protection devices (surge arrestors, current limiting inductors, etc…) is not analyzed.

However, there is considered the use of passive resonant filters as blocking filters to modify the frequency response of the system, because, in this way, it is possible to evaluate the transient oscillations phenomena. Due to the fact that these filters are oriented to change the frequency response of the system, in order to avoid the transient oscillations and over-voltages.

7.3.3.1 Fault clearance in the inter-turbine grid with passive filters

When a circuit breaker interrupts a current, even at zero current, it causes a transient. This transient is caused by the system adjusting itself to an emerging different configuration of components, as is explained in section 7.1.

In circuits with inductive-capacitive components, the transient has oscillations. The energy exchange between the inductive component and the capacitive component of the circuit produces an oscillation at the resonance frequency.

A simple method to mitigate those oscillations and over voltages is to install a blocking filter in series with the generator and the step-up transformer winding or connected to the neutral point of the high voltage side of the transformer [125].

Thus, if a RLC passive filter is adjusted at this resonance frequency, the oscillating energy between those components is deviated to the filter to be consumed in its resistive part.

For the considered base scenario, the oscillation is caused mainly by the iteration between the leakage inductance of the step up transformer in the offshore platform and the capacitive component of the inter-turbine cables. The inter turbine cables are connected in parallel to the collector point, thus, the total capacitive component of the inter turbine grid, is the addition of the capacitive components of all the inter turbine cable segments. As a result, with more capacitive impedance in parallel, the frequency of the resonance decreases.

The disconnection of a complete feeder from the breaker suited in the offshore platform, changes the morphology of the system, as well as the equivalent impedance of the circuit. So, the number of feeders connected to the PC determines the voltage peak and the oscillation frequency of the transient caused by the disconnection of a feeder.

Therefore, in this section, the frequency response variations due to the changes in the inter turbine grid are analyzed. More specifically, the frequency response variation changing the considered wind farm from five feeders connected to only one feeder connected.

To perform the harmonic analysis of the system, in the same way of the previous chapter 6, in this chapter too, the frequency response of the equivalent scenario is estimated using a harmonic source. Furthermore, also the same harmonics train of the previous chapter (Figure 6.2) is used.

In the present case, the scenario to estimate the frequency response is shown in Figure 7.15.

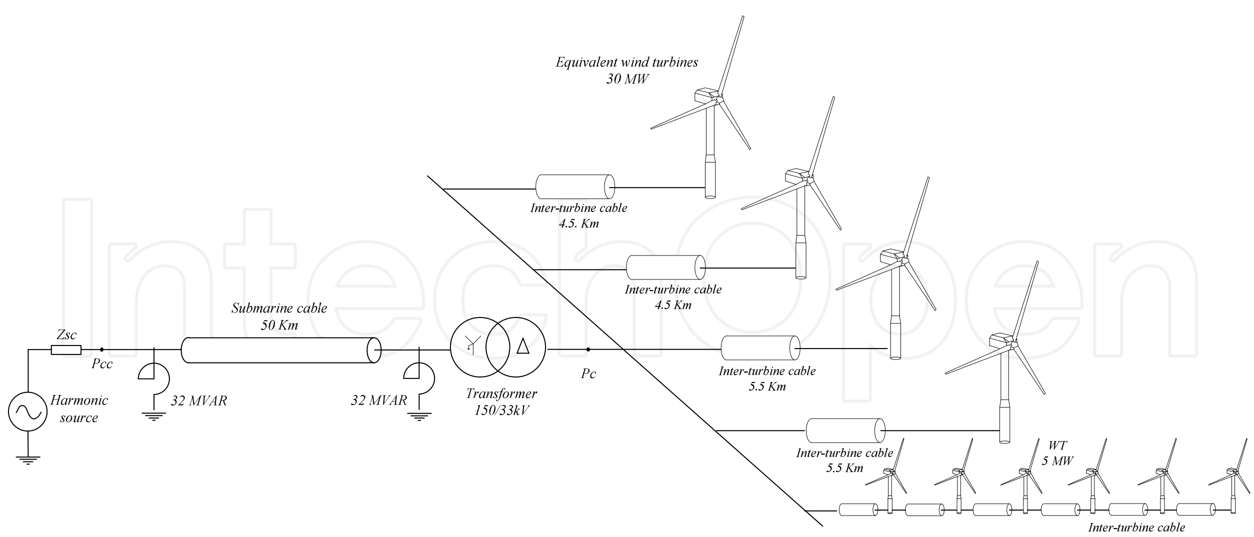


Figure 7.15 The scheme to estimate the frequency response of the considered scenario to evaluate disconnections of wind turbines and feeders.

The results for the scenario displayed in Figure 7.15, varying the number of feeders connected to the PC are summarized in Figure 7.16.

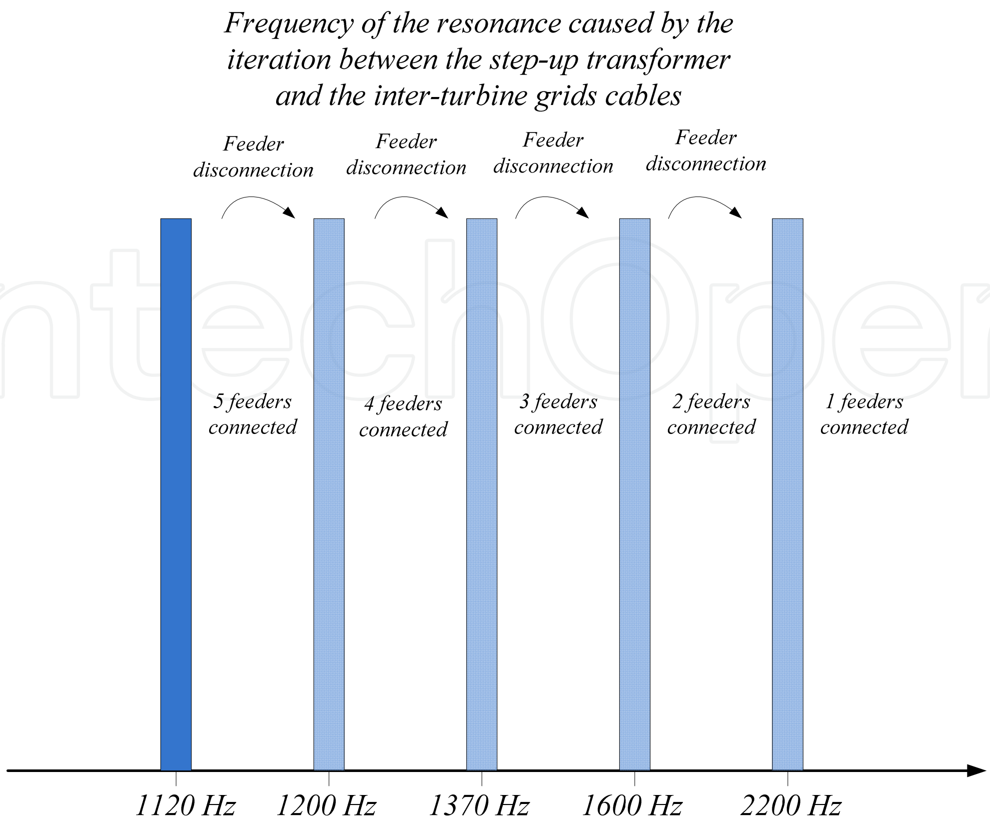


Figure 7.16 Frequency of the resonance caused by the iteration between the step-up transformer and the inter turbine cables depending on the number of feeders connected to the PC.

A wind turbine disconnection does not change the electrical structure of the system as much as a disconnection of a feeder. In case of wind turbine disconnections, parallel impedance is disconnected from the electric infrastructure. Therefore, the system has not huge variation, still has a similar frequency response, as can be seen at the results summarized in Figure 7.17.

The objective is to change the frequency response of the system, to eliminate or attenuate the resonances and avoid the harmonic amplifications and instabilities to the system. For that purpose, for each one of the frequencies with the potential to amplify harmonics must be placed a passive filter. Thus, the passive filters are tuned to filter the resonance frequencies of the complete offshore wind farm and for its possible variations.

In this way, passive filters to avoid resonances of the system are placed for each possible combination, i.e. a passive filter adjusted at 1200Hz is placed to avoid the oscillation caused for the resonance of the system when the wind farm is operating with four feeders connected, another filter adjusted at 1370Hz is placed to avoid the oscillation caused for the resonance of the system when the wind farm is operating with three feeders connected, etc…In short, five passive filters are placed to avoid the resonances for all the possible cases and combinations of the offshore wind farm.

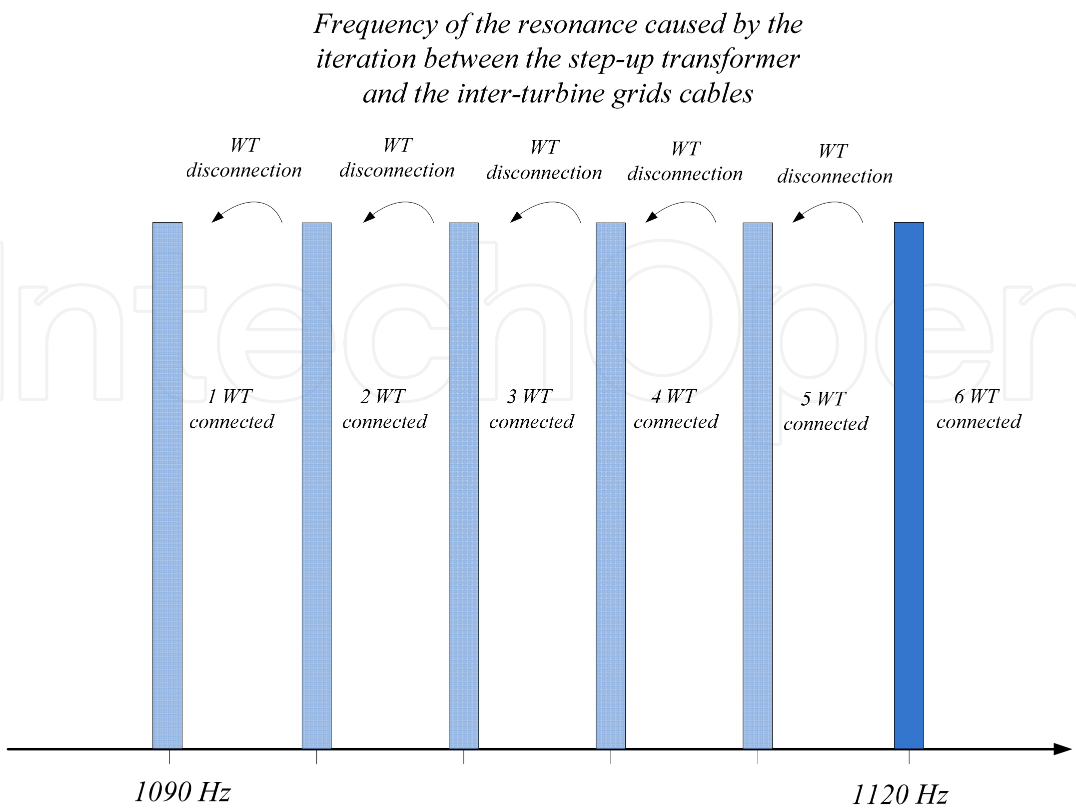


Figure 7.17 Frequency of the resonance caused by the iteration between the step-up transformer and the inter turbine cables depending on the number wind turbines connected to the feeder.

The passive filters are adjusted based on the following characteristics: reactive power generated at 50 Hz 3 MVAR, rated current of the RLC branch 1000A (Imax at resonance frequency). To know how are adjusted the passive filters see Appendix E: Resonant Passive Filters. The characteristics of the used passive filters are shown in Table 7.1

Fresonance	R	L1	L2	C	Ploss (50Hz)	
1100 Hz	19 Ω	1.65 mH	7.95 mH	8.3765 μF	2.5 kW	0.0016 p.u
1200 Hz	19 Ω	1.37 mH	7.95 mH	8.3765 μF	2.5 kW	0.0016 p.u
1370 Hz	19 Ω	0.927 mH	6.36 mH	8.3765 μF	2.5 kW	0.0016 p.u
1600 Hz	19 Ω	0.665 mH	6.36 mH	8.3765 μF	2.5 kW	0.001 p.u
2200 Hz	19 Ω	0.259 mH	4.77 mH	8.3765 μF	2.5 kW	0.0006 p.u

Table 7.1 Characteristics of the passive filters used to improve the transients during disconnections.

The passive filters, as well as the inter-turbine cable generate capacitive reactive power. If this reactive power is not compensated, the step-up transformer has to be oversized. Therefore, depending on the number of passive filters and the reactive power generated by them, an inductive static reactive power compensator has to be placed.

In this way, in the present section, the simulations are carried out taking into account the five passive filters and their associated reactive power compensation, Figure 7.18.

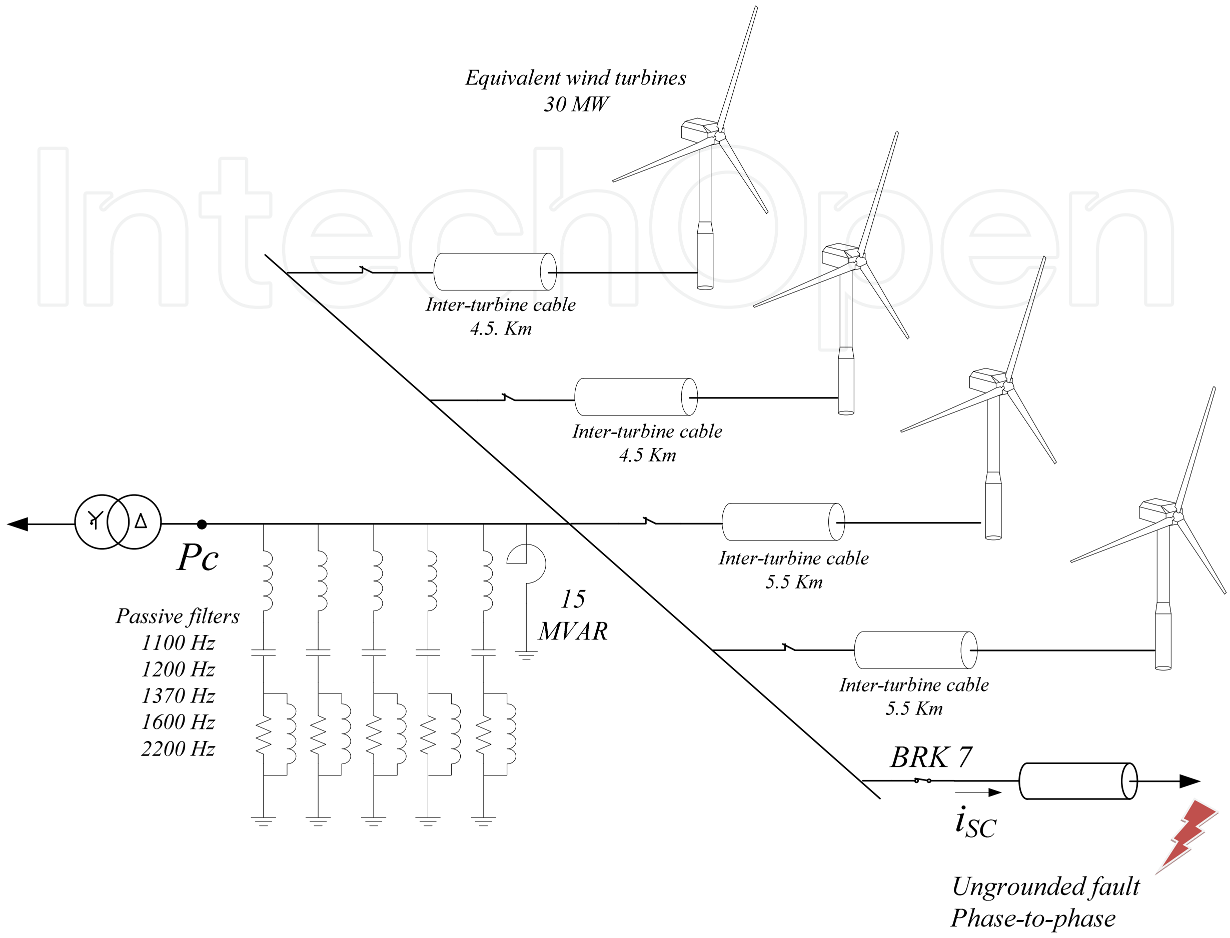


Figure 7.18 The scheme of the simulation scenario to evaluate the effect of the disconnection of a feeder during a short circuit fault.

To evaluate if the passive filters improve the transient response of the system, the disconnection of a feeder during a fault is simulated. As in the previous section, after 60ms (3 cycles) of short circuit (0.9s), the breaker interrupts the current at zero crossing instant. The simulation results of the base scenario with passive filters for this first case are depicted at Figure 7.19.

Therefore, from the simulation results displayed on this section, it can be concluded that the use of passive filters adjusted at the resonances of the offshore wind farm avoids the high frequency transients and reduce current / voltage peaks at breaker open operations.

The reduction of the high frequency components of the transient have a considerable importance, because as is mentioned before, according to some studies the high frequency transients are the cause of the transformer insulation failures [121]. Although, the direct proof of the negative impact of the high frequency transients on the transformer insulation is not yet found [124].

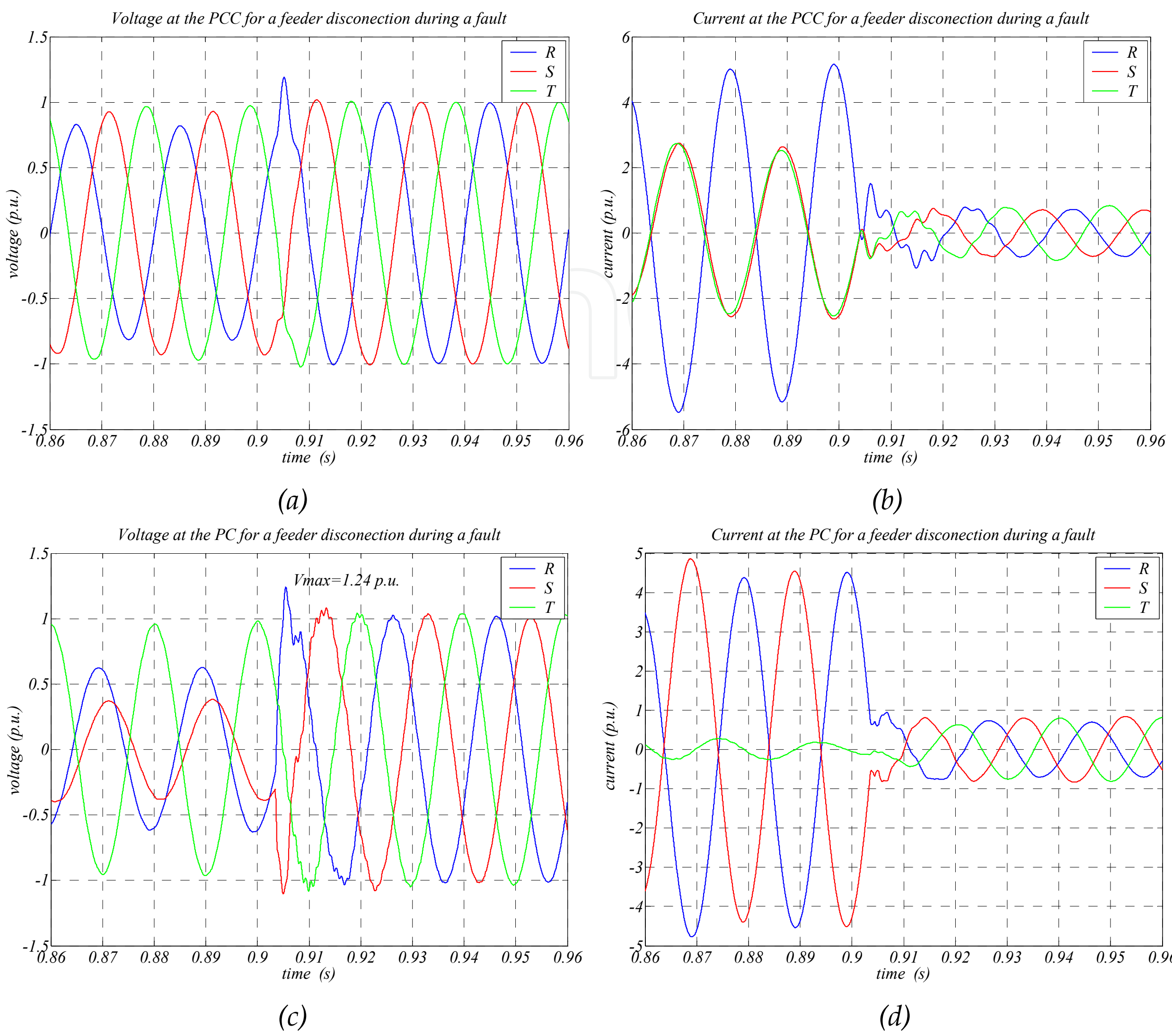


Figure 7.19 Three-phase signals (current and voltage) at the main points of the considered wind farm with passive filters when the disconnection of a feeder occurs during a fault.

7.4 Evaluation of the voltage dips in the PCC (LVRT)

The term LVRT is used to describe the capability of an electric system (in this case the offshore wind farm) to get over the voltage dips.

A voltage dip is a sharp voltage reduction down to 90-10% of the RMS voltage magnitude of one phase (or several) with a quick recuperation of the nominal values. So, a voltage dip can be described using two parameters: the depth and the duration.

Focusing on wind power based generation systems, the behavior of these types of generation plants during any eventuality, which causes a voltage drop at the point of common coupling (PCC), is crucial to ensure the quality and the continuity of the electric supply.

If due to a voltage disturbance in the grid, like a voltage dip, all the wind generation systems have been disconnected from the grid. After the clearance of the fault, there will not be enough active power to supply the consumption, which can cause the collapse of the distribution grid.

Thus, in order to avoid the collapse of the distribution system, the wind generation systems have to be provided with the capabilities to remain connected to the grid during voltage dips in the PCC. Furthermore, wind generation systems have to help the distribution system during the faults to recover the normal operation.

Therefore, if this kind of generation systems wants to be connected to the distribution grid, they have to satisfy the grid code requirements of the system operator (SO).

Transmission system operators often put strict requirements on the low voltage ride through (LVRT) of wind power plants. The specific details of the requirements differ significantly between transmission system operators. However, it is possible to find in them some common features on voltage ride trough. Roughly, the behavior required to wind farms by international grid codes for voltage dips in the PCC has the following common specifications

- The tripping of the energy generation resource as a result of these short-term faults should be prevented, i.e. all the wind turbines of the wind farm must remain connected to the grid during any voltage dip (at the PCC) within the boundaries displayed at Figure 7.20.
- During the fault, the wind farm must support the grid voltage increasing the injected capacitive reactive current to the PCC.
- After the clearance of the fault, the wind farm must recovery the injected active power to the values before the fault fast and in an orderly way. In other words, the wind power plant production should recover to its pre-fault value within a certain time after the clearing.

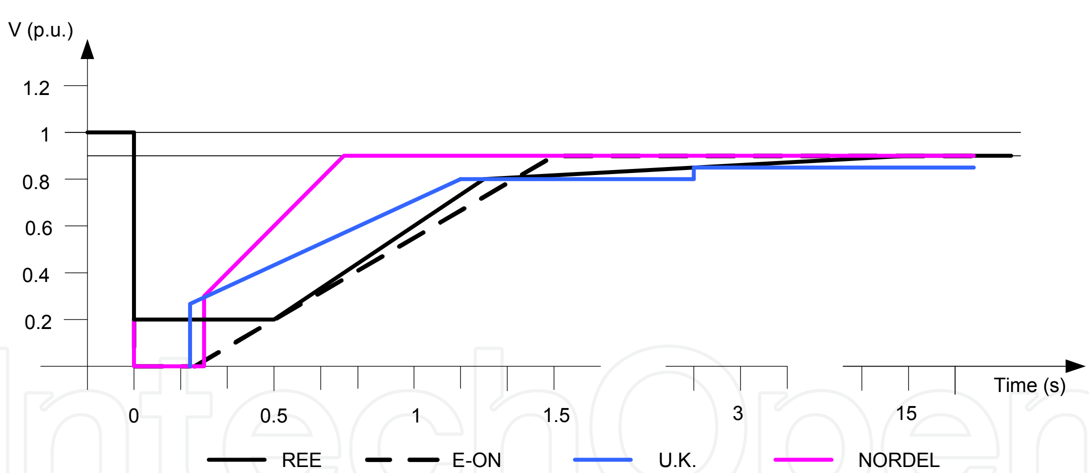


Figure 7.20 Profile of the voltage dips that a wind turbine must remain connected for several grid codes.

In order to focus the analysis, the REE grid code (see Appendix C: REE Grid Code Requirements for Voltage Dips) is the only one taken into account. Looking to the REE grid code, the requirements upon a voltage disturbance at the PCC are basically two: Firstly, ensure that the generating facilities remain on-line (in order to a fast recovery to pre-fault values) and secondly help restoring system voltages.

This can be achieved by all the various wind turbine technologies, but exactly how it is achieved depends of the type of wind turbine technology. Without low-voltage ride-through

(LVRT) capability most wind turbine generators (irrespective of manufacturer or type) will trip during a system disturbance. So, the LVRT capability is a necessary feature on all wind turbine generators to remain the wind farms connected to the transmission grid.

For the case of wind turbines with full-scale converters, this kind of wind turbines supplies all the generated power through the converters. Thus, in the event of voltage dips in the grid, the grid side converter switches to reactive power priority, as a result, the active power injected by the converter can be reduced.

In short, if the wind turbine is able to ride through a disturbance and the necessary control and protection modifications have been made to ensure for fault ride-through, then the wind turbines will respond producing the required reactive power to restore voltage or at least a big part of it.

The considered scenario fits in this last case, all the wind turbines installed in the offshore wind farm can fulfill individually the REE grid code requirements for LVRT, as is verified in section 5.2.2.4. Consequently, an offshore wind farm composed by this kind of turbines with full-scale converters may be capable to fulfill the grid code requirements or at least be close to fulfilling such demands.

Therefore, in the present section, several simulations are carried out to analyze the behavior of the considered wind farm. The objective of this analysis based on simulations is to determine if the considered offshore wind farm (chapter 5) with this type of wind turbines can fulfill the grid code requirements and if it cannot, why not and how far is it. Then on the basis of the simulation results, purpose a solution to fulfill those requirements.

7.4.1 Evaluation of the grid code fulfillment of the considered wind farm for voltage dips at the PCC

In this section, firstly, the behavior of the developed wind farm model (see section 7.2) during a three-phase voltage dip at PCC is evaluated. With the objective to determine if it can fulfill the REE grid code requirements.

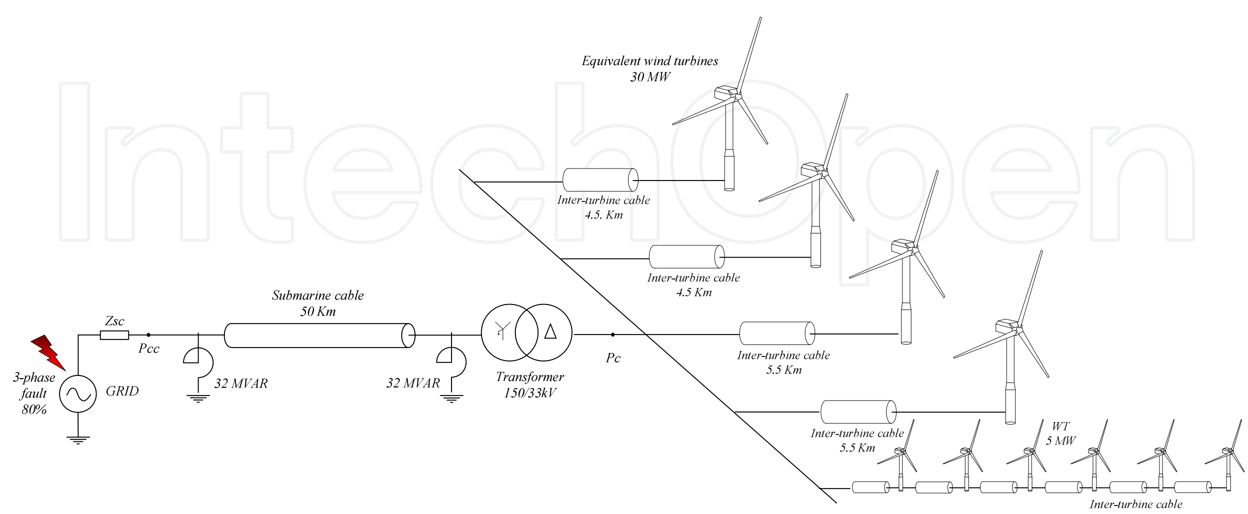


Figure 7.21 The simulation scenario to evaluate the behavior of the wind farm upon voltage dips.

For that purpose, upon the considered offshore wind farm, a three-phase voltage dip of 80% at the PCC (the most severe 3-phase fault considered by the REE grid code) is applied. To focus the analysis in the worst case is considered that all the wind turbines are operating at full-load (Table 5.13), at 90% of the rated power with a unity power factor. The simulated scenario is depicted in Figure 7.21. The voltage, current and power at the PCC obtained in the simulation of the considered scenario is shown at Figure 7.22.

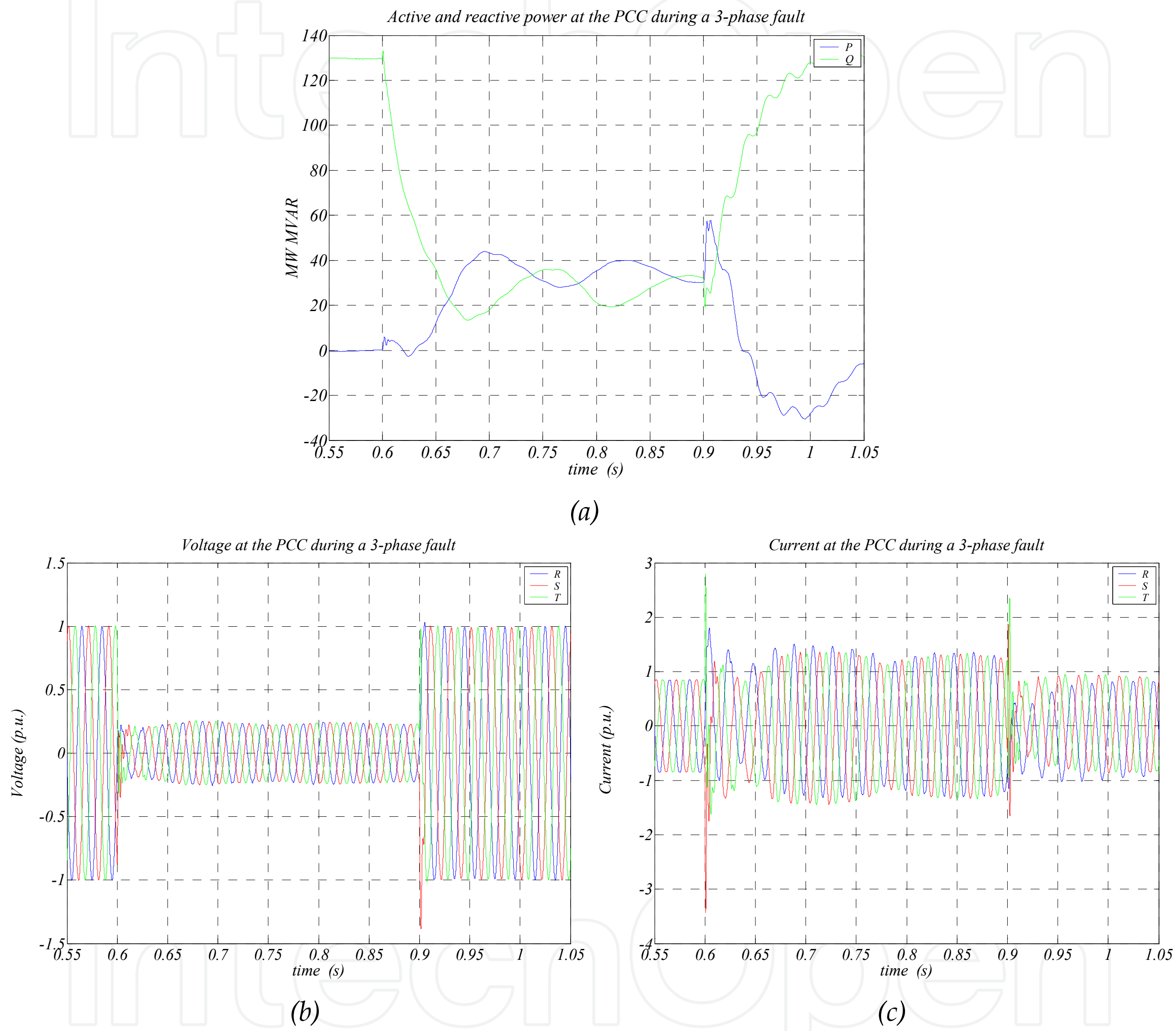
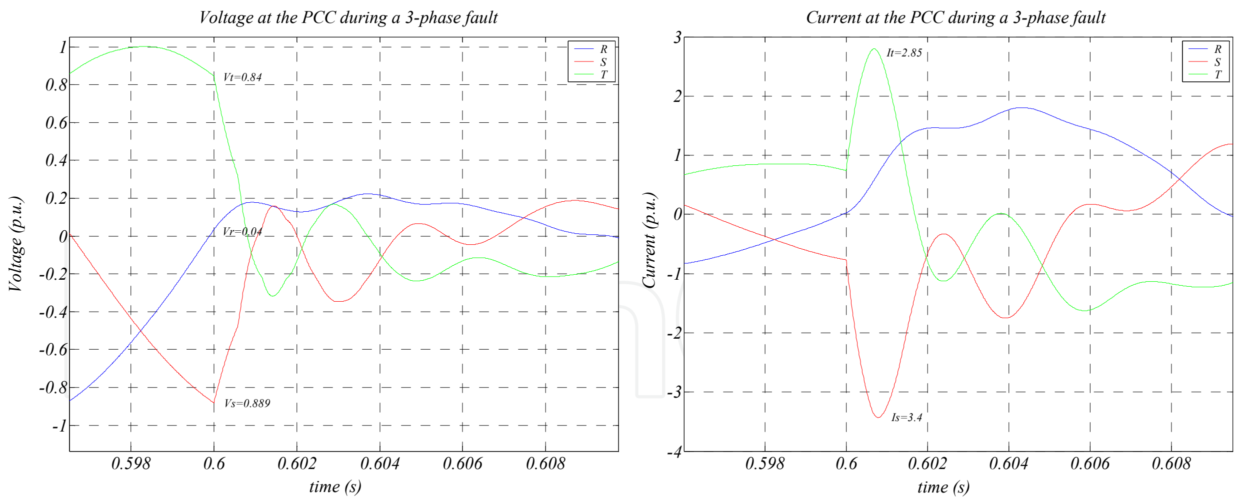


Figure 7.22 Current, voltage and active /reactive power at the PCC for the considered simulation scenario upon 3-phase 80% dip.

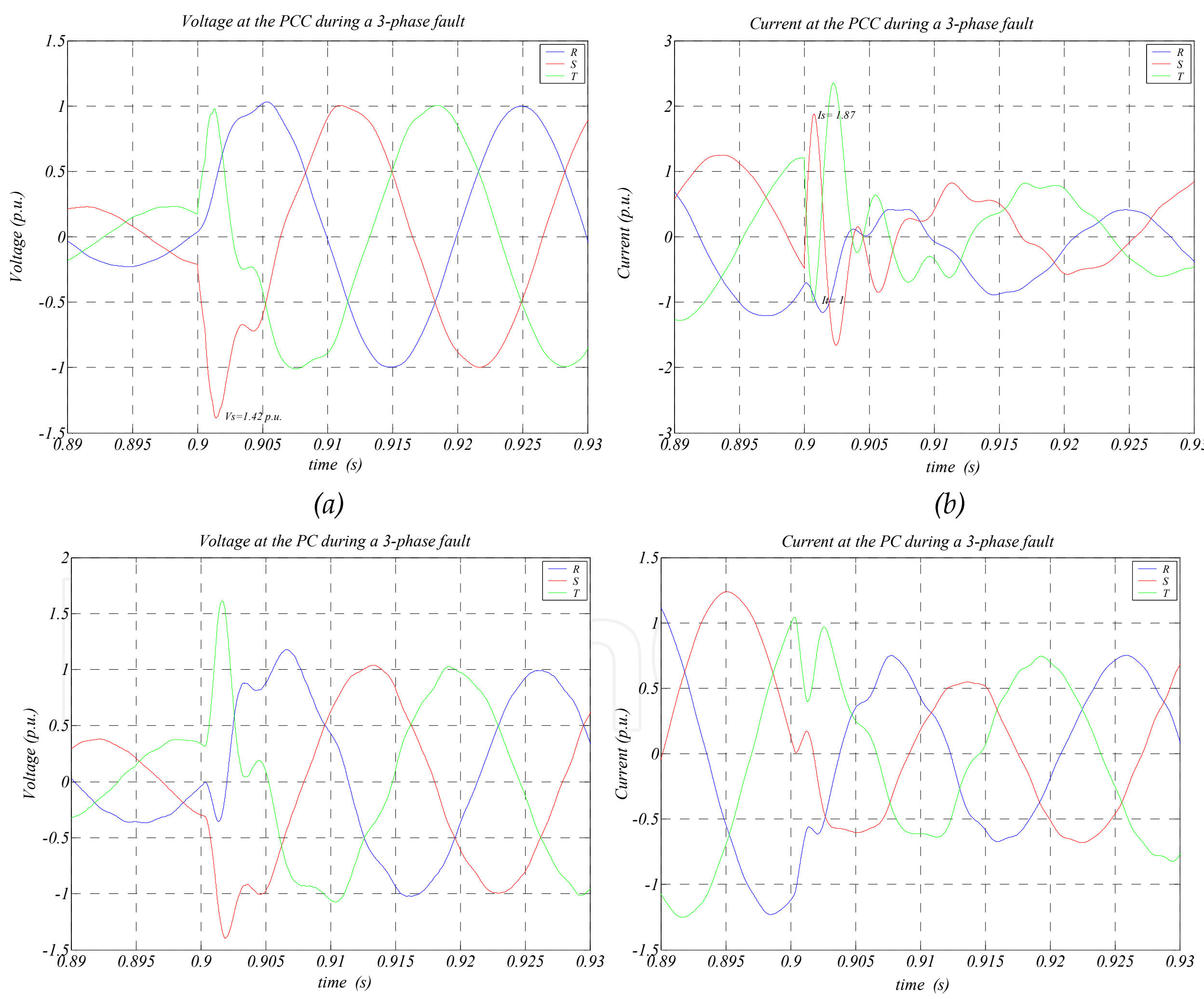
In first place, the tripping of the wind turbines and the protection of its integrity due to the current / voltage peaks in the transmission system is discussed. Thus, the current peaks at the beginning of the fault and just in the clearance of the fault (Figure 7.22 (*c*)) are evaluated.

Those current peaks are exactly in the phases where the capacitive component of the submarine cable is charged and the magnitudes of the current peaks are also proportional to the phase voltages (see Figure 7.23).



(a) (b)

Figure 7.23 Current and voltage in detail at the PCC when the fault happens (0.6s).



(a) (b)

(c) (d)

Figure 7.24 Current and voltage in detail at the PCC *(a)* – *(b)* and PC *(c)* – *(d)*, when the fault is cleared (0.9s).

At the fault clearance occurs something similar, the bigger is the voltage step, the bigger is the needed current to charge the capacitive component of the cable. In other words, at the fault clearance, the phase voltage steps to the same point of the sinus but to the nominal voltage. Thus, the closer is the phase voltage to the maximum peak value, the bigger is the voltage step of this phase and the bigger is the inrush current, Figure 7.24 *(a) - (b)*.

Therefore, the circuit has the typical inrush currents for the energizing / de-energizing of the cable, in concordance with the results described in [126] and in section 7.1. So, it is possible to conclude that those current peaks are inherent to the capacitive behavior of the submarine cable upon fast voltage changes.

Looking to the voltage peaks (Figure 7.24, *(a) - (c)*), it is possible to see over voltages at the cable energizing, in the same way that is described in section 7.1 for the analysis of the submarine cable energizing.

The maximum value of the peaks and their duration is a key issue, because all the equipment of the wind farm must remain connected during the voltage fault. Therefore, in the next step of the evaluation, these voltage / current peaks are characterized

The voltage and current peaks in the main points of the offshore wind farm are summarized in Table 7.2 and the three-phase signals are displayed at Figure 7.22 and Figure 7.25. The duration of the voltage / current peaks are measured from the instant when the signal overcomes its nominal values to the instant when the signal comes back to its nominal values.

Xsc=5%				
PCC				
Phase	*Current*		*Voltage*	
	Maximum peak	*duration*	*Maximum peak*	*duration*
Phase R	*1.85 In*	*1.7 ms*	-	-
Phase S	*3.4 In*	*1.8 ms*	*1.4 Vn*	*1.5 ms*
Phase T	*2.8 In*	*1.4 ms*	-	-
PC				
Phase R	-	-	*1.2 Vn*	*1.5 ms*
Phase S	-	-	*1.41 Vn*	*1.6 ms*
Phase T	-	-	*1.62 Vn*	*1.4 ms*
At the WT terminals				
Phase R	-	-	*1.3 Vn*	*2 ms*
Phase S	-	-	*1.21 Vn*	*3 ms*
Phase T	-	-	*1.7 Vn*	*1.7 ms*

Table 7.2 Characteristics of the voltage and current peaks at the main points of the simulation scenario.

The current amplitude oscillations during the maintenance of the fault, which can be seen at Figure 7.25 *(b)-(d),* are caused by the voltage difference at the wind turbine terminals. Each wind turbine see a different impedance depending on its location in the inter turbine grid. In normal operation (rated voltage at the PC), this difference is not significant.

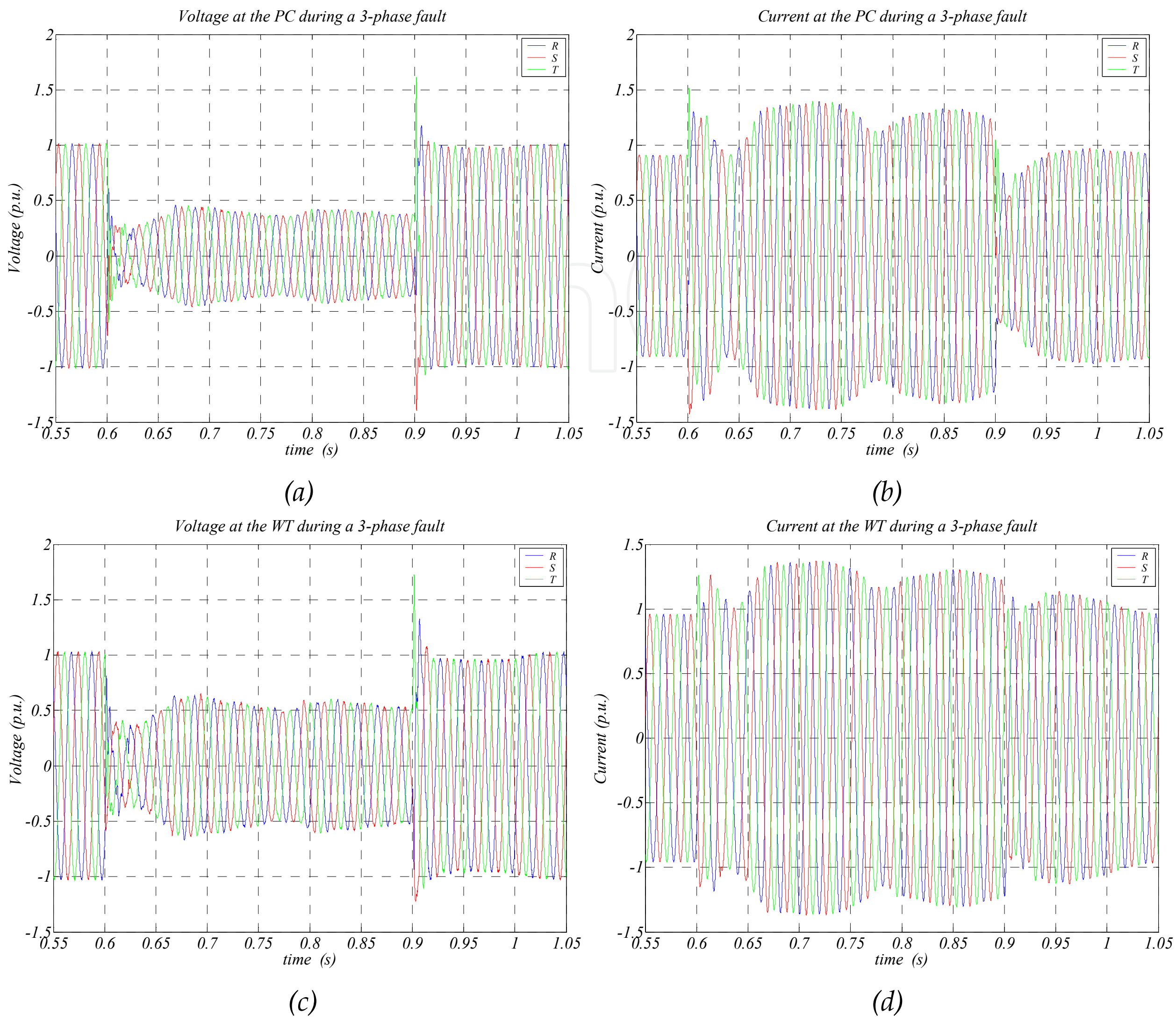


Figure 7.25 Current and voltage at the PC *(a)* – *(b)* and wind turbine terminals *(c)* – *(d),* three-phase signals.

However, this difference increases in voltage dips, due to the fact that the wind turbines are supporting the voltage at the PC. Furthermore, this difference increases as a step when the fault occurs. Thus, the wind turbine converters need time to synchronize and stabilize the current at the PC.

The considered wind turbine model allows temporary over currents during the faults, consequently, the current during voltage dips increases to 1.2 p.u., as can be seen at Figure 7.25 *(b)-(d).*

As is mentioned in section 7.1, the current/voltage peaks are provoked by the capacitive component of the submarine cable, these current peaks (submarine cable energizing / de-energizing inrush current peaks) depends on two variables: the voltage drop/step and the series impedance between the submarine cable and where the voltage drop/step occurs.

The voltage drop/step depends on the fault and the maximum depth is determined by grid codes, but the grid impedance depends on the point of the grid that the offshore wind farm is connected.

Xsc=15%				
PCC				
Phase	*Current*		*Voltage*	
	Maximum peak	*duration*	*Maximum peak*	*duration*
Phase R	*1.85 In*	*0.7 ms*	-	-
Phase S	*2.6 In*	*3 ms*	*1.36 Vn*	*2 ms*
Phase T	*1.77 In*	*1.8 ms*	-	-
PC				
Phase R	-	-	*1.2 Vn*	*2.8 ms*
Phase S	-	-	*1.3 Vn*	*2.3 ms*
Phase T	-	-	*1.15 Vn*	*1.2 ms*
At the WT terminals				
Phase R	-	-	*1.16 Vn*	*3.3 ms*
Phase S	-	-	*1.2 Vn*	*2.6 ms*
Phase T	-	-	*1.32 Vn*	*1.8 ms*

Table 7.3 Characteristics of the voltage and current peaks at the main points of the simulation scenario.

In the present case, a strong grid point is chosen. Nevertheless, not all the wind farms have to connect to a strong grid. It is possible that some offshore wind farms have to connect for example to a point with bigger grid impedance.

In this way, to evaluate this point, the voltage and current peaks in the main points of the base offshore wind farm (Figure 7.21) considering a short circuit impedance of 15% is estimated. The results are summarized in Table 7.3

Regarding to Table 7.2 and Table 7.3, it can be seen how with bigger short circuit impedance, the maximum peak value in the fault transient decreases. So, the short circuit impedance has an important role on the cable energizing / de-energizing. In this way, using auxiliary devices to limit the current during fault conditions (such as current limiting reactors) [127], it is possible to achieve the same effect.

The current peaks appear only at the PCC with a short duration. Considering that the over current protection systems are adjusted for a specific thermal limit, the shorter is the peak, the less dangerous is for the system. Furthermore, the inrush currents of the transformer (as for the submarine cable) are 3-5 times bigger than the nominal current. Therefore, the protection devices have to be dimensioned for current peaks with these values.

On the other hand are the voltage peaks. Upon this type of peaks the most vulnerable equipments / components are those ones based on power electronics. Looking at the maximum peak value of the over voltages, 1.7 - 1.3 times the nominal voltage at the wind turbine terminals, these values are quite dangerous for the integrity of the power electronic devices. Thus, this kind of devices must be provided with the proper protection circuits.

However, considering that the voltage and current peaks measured in simulation are not dangerous for the main elements of the transmission system: Step-up transformer (not due to the peak value), submarine cable and inductive compensators.

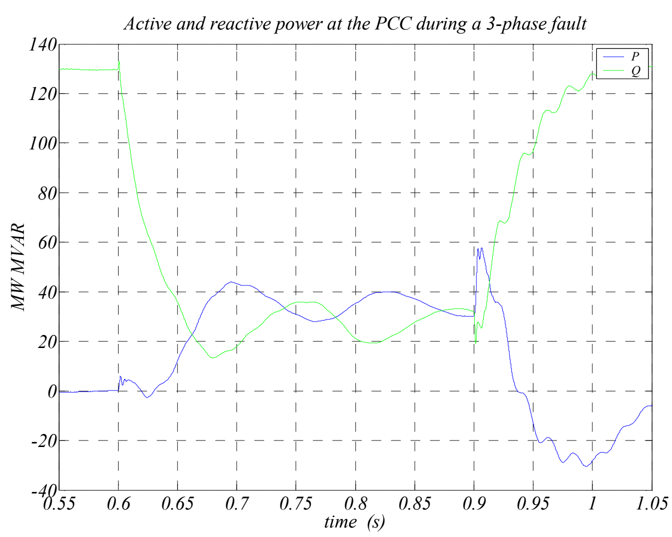
Those transient over voltages are a matter of the wind turbine design (grid side converters protections), which is not considered as one of the objectives of the book. Consequently, the characterization of those protection devices is not analyzed.

7.4.1.1 Reactive power injection at the PCC during voltage dips

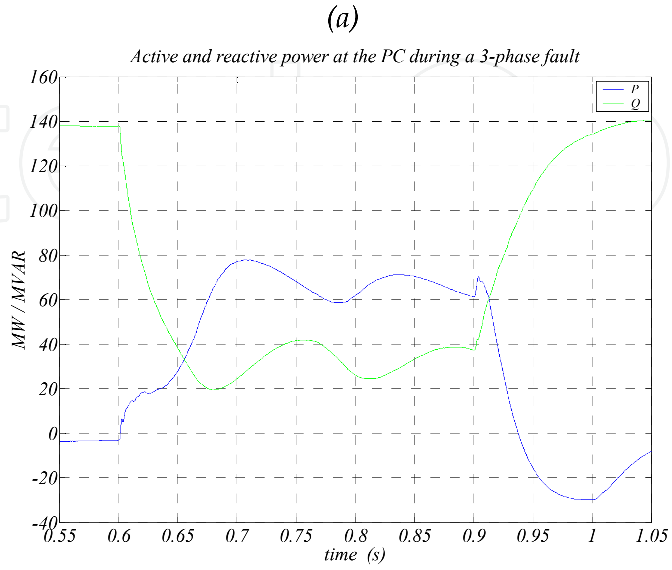
Apart from the protection of the integrity of the system and avoid the tripping of the wind turbines, the other main issue of the wind farms to fulfill the LVRT requirements is the injection of the proper reactive current at the PCC.

Looking at the results displayed at Figure 7.22, it is possible to conclude at first sight that the wind farm does not fulfill the grid code requirements. Due to the fact that the injected active and reactive-capacitive power to the distribution grid at the PCC is similar, unless predominately reactive-capacitive.

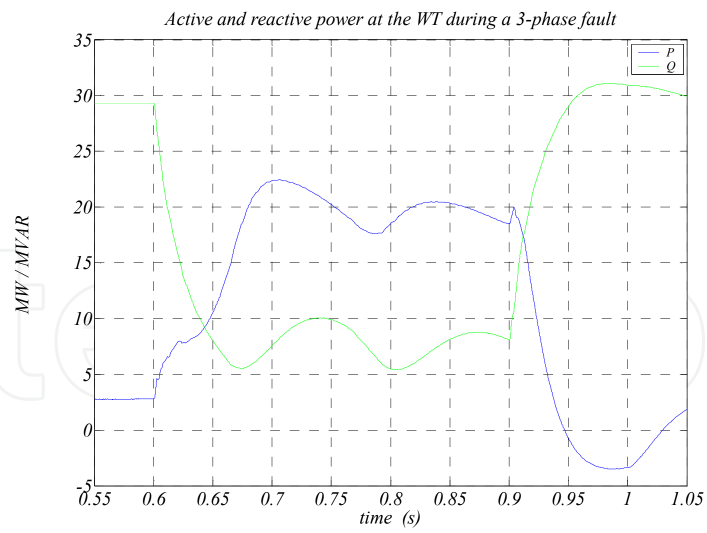
To analyze this aspect, the evolution of the active and reactive power in the main point of the offshore wind farm is depicted in Figure 7.26.



(a)



(b)



(c)

Figure 7.26 Active and reactive power at the main points of the simulation scenario, *(a)* PCC, *(b)* PC and *(c)* at the terminals of the wind turbine.

The offshore wind farm does not accomplish with the required reactive current injection for two reasons: The wind turbine does not inject the proper reactive current in relation to the active current (Figure 7.26 *(c)*) and the transmission system generates inductive reactive current (Figure 7.26 *(a)* - *(b)*).

The behavior of the wind turbines upon voltage dip is verified at 5.2.2.4. However, as can be seen in Figure 7.26 *(c)*, the wind turbines do not inject the reactive current in the correct quantities. One reason for this reduction is the difference between the voltage at the terminals of the wind turbines and the PCC. The voltage at the wind turbine terminals is significantly higher than at the PCC.

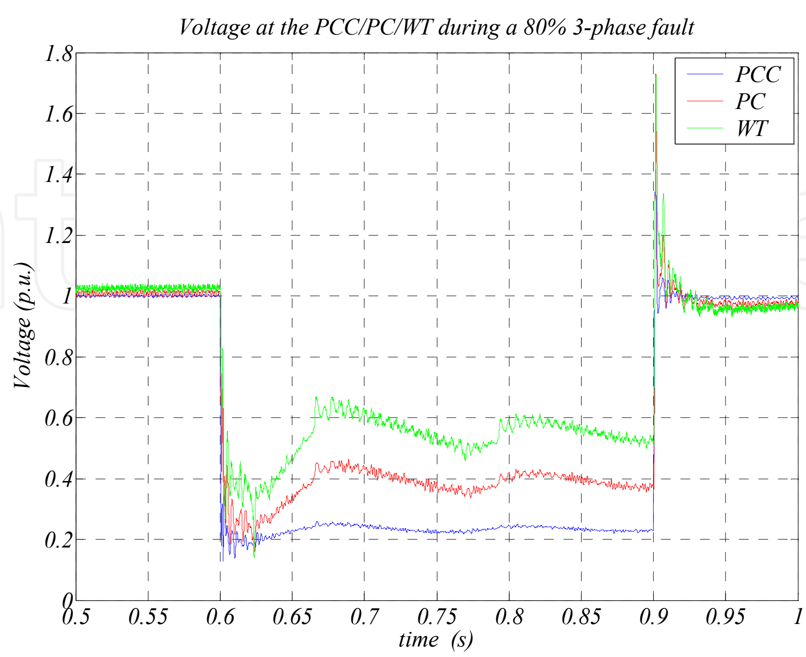
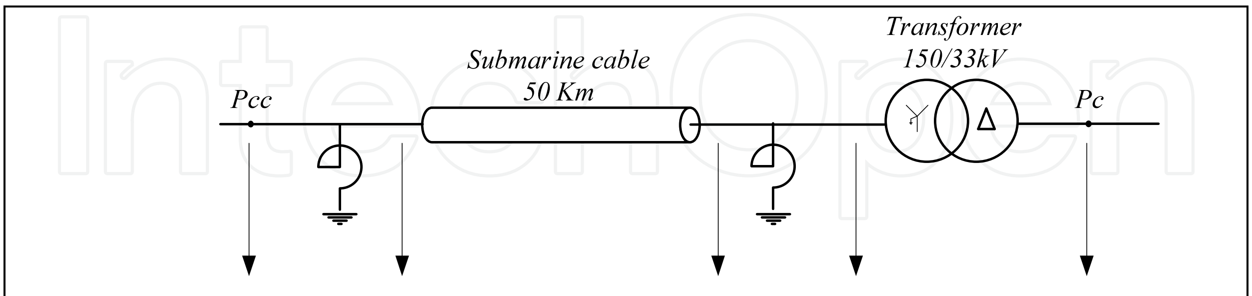


Figure 7.27 Voltage module at the main points of the system during a 3-phase 80% voltage dip.

The wind turbines have in their terminals a 50% voltage dip unless the 80% of the PCC, as can be seen in Figure 7.27.

Continuing with the analysis, why the transmission system generates inductive reactive power (Figure 7.26 *(a)* - *(b)*) is evaluated. For that purpose, the active and reactive power values of all the points of the transmission system are summarized on Table 7.4.



Normal operation					
P	*131 MW*	*132 MW*	*133 MW*	*135 MW*	*138 MW*
Q	*0 MVAR (c)*	*29 MVAR (c)*	*50 MVAR (i)*	*17 MVAR (i)*	*3 MVAR (i)*
During the voltage dip					
P	*33 MW*	*33 MW*	*35 MW*	*36 MW*	*38.5 MW*
Q	*31 MVAR (c)*	*33 MVAR (c)*	*36 MVAR (c)*	*39 MVAR (c)*	*65 MVAR (c)*

Table 7.4 Active and reactive power at all the points of the transmission system during an 80% 3-phase voltage dip, (i) inductive reactive power and (c) capacitive reactive power.

From the results displayed on Table 7.4, it is possible to see a reactive-capacitive power reduction between the two ends of the submarine cable during the voltage dip unless an increment. Therefore, with a huge voltage reduction, the submarine cable can generate inductive reactive power depending on the current through the cable.

Using the equations (98) and (99), see section 4.3.2.2, it is possible to estimate the reactive power generated in the submarine cable. Thus, considering a reduction of 80% on the applied voltage to the cable while flows the rated current, equations (145) and (146), the submarine cable generates 2.22 MVAR (0.74 MVAR per phase) of inductive reactive power (with rated current plus 10% 3 MVAR).

$$Q_C = \frac{|V_C|^2}{|X_C|} = \frac{|17.3kV|^2}{|273\Omega|} = 1MVAR \tag{145}$$

$$Q_L = |I_L|^2 \cdot |X_L| = |577\,A|^2 \cdot |5.24\Omega| = 1.74\,MVAR \tag{146}$$

7.5 Proposed electrical connection infrastructure

From the evaluation of the previous section is known that the voltage dips at the PCC does not causes dangerous over voltages for the offshore wind farms connection electric infrastructure (step-up transformer, cable, compensators, etc…), but these voltage peaks can be dangerous for the electronic devices.

The first step to fulfill the grid code requirements is to avoid the tripping of the system during grid faults. Thus, in the proposed solution is considered that the converters have well adjusted their protections. Consequently, it is considered that the offshore wind farm will not trip during voltage dips. However, the protection devices of the wind turbines are not considered in detail.

Therefore, this section is focused on the injection of the proper reactive-capacitive power at the PCC, the other main issue of the wind farm to fulfill the LVRT requirements, as is exposed in the previous section.

7.5.1 Modification of the Ireactive / Itotal curve of the wind turbines

As is shown in Figure 7.26, the wind turbines do not inject the required reactive current due to the voltage difference between the PCC and wind turbine terminals (Figure 7.27).

One solution for this problem can be the modification of the Ireactive / Itotal curve depending on the voltage of each wind turbine (see Appendix C: REE Grid Code Requirements for Voltage Dips Figure C.3). This modification has to be oriented to fulfill the grid code curve at the PCC, not at the wind turbine terminals. So, the voltage limits of the curve have to be adjusted considering the propagation of the voltage dip trough the transmission system.

To carry out the adjustment of the voltage limits for the Ireactive / Itotal curve on the considered scenario, several symmetric voltage dips with key depth are simulated in order to know how voltage dips are propagated. The simulation scenario to evaluate the voltage dips propagation is depicted on Figure 7.28.

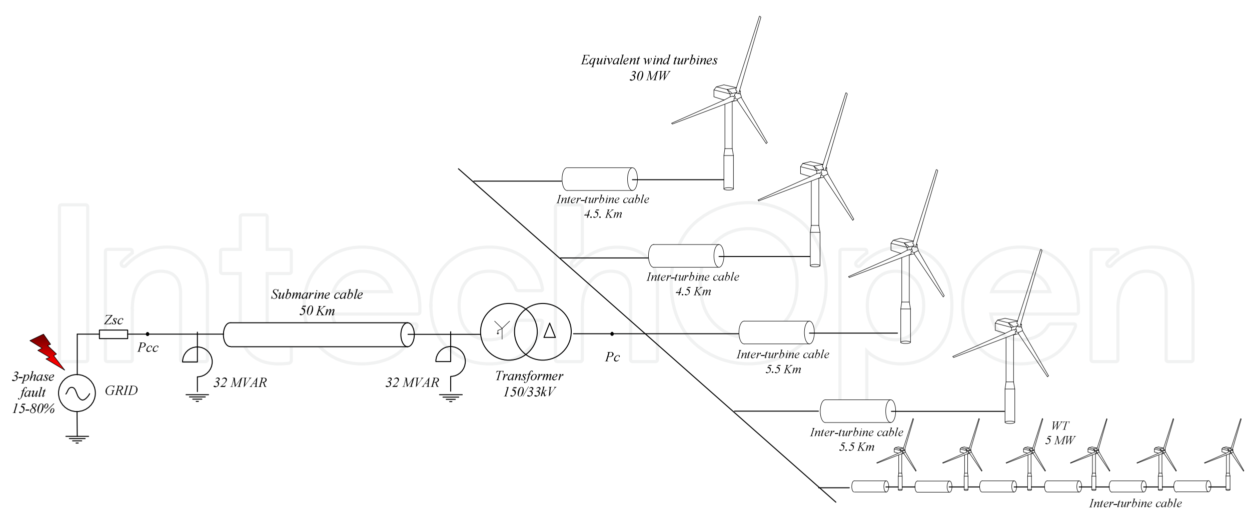
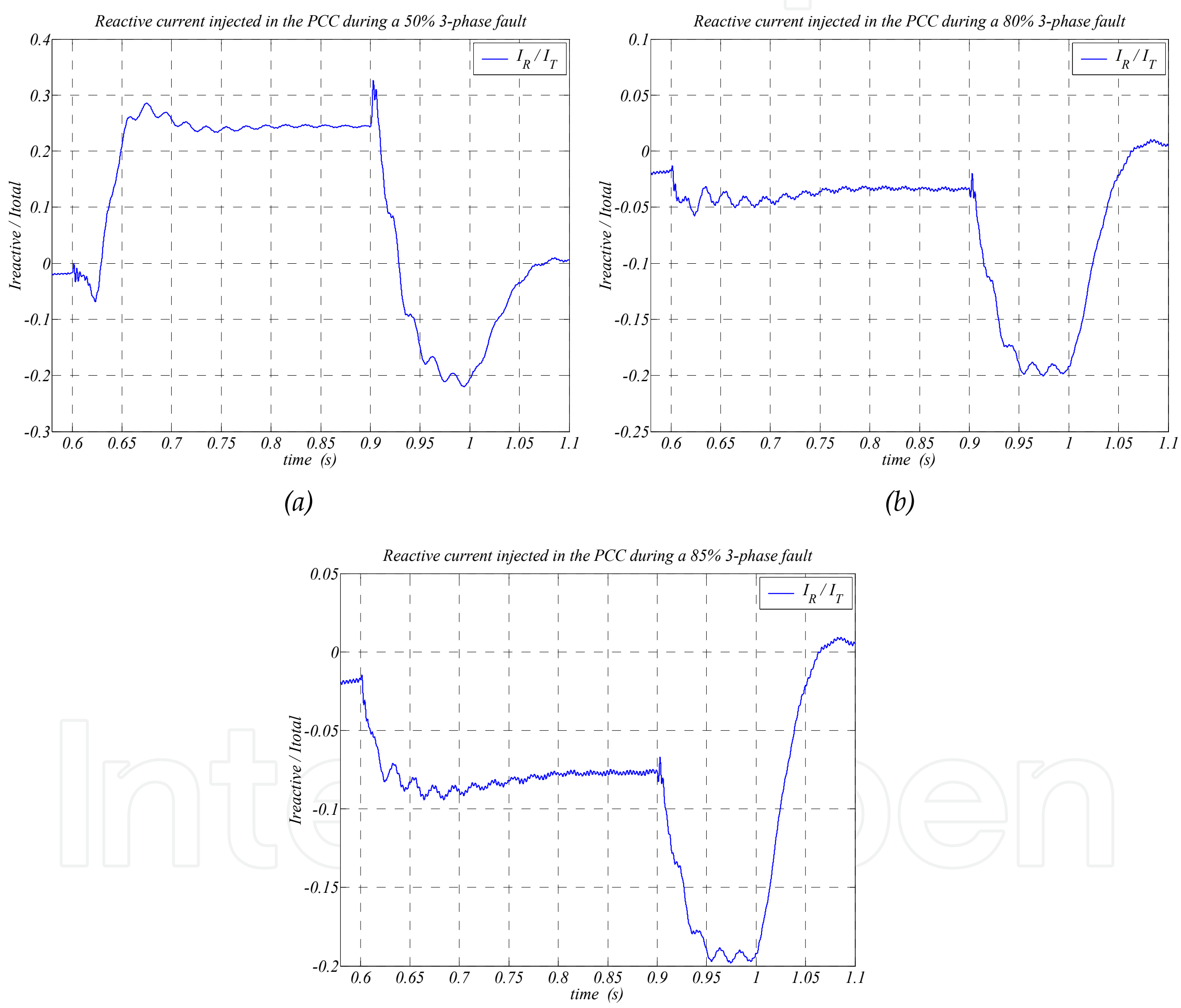


Figure 7.28 The simulation scenario to evaluate the behavior of the wind farm upon voltage dips.

The evolutions of the voltage through the electric infrastructure for voltage dips with the key depths are summarized in Table 7.5 and the Ireactive / Itotal ratio at the PCC for those voltage dips in Figure 7.29

At PCC	*At PC*	*At WT terminals*
A 3-phase voltage dip with 80% of depth *Vpcc=0.2 p.u.*	*60 % of depth* *Vpc=0.4 p.u.*	*48% of depth* *Vwt=0.52 p.u.*
A 3-phase voltage dip with 50% of depth *Vpcc=0.5 p.u.*	*40% of depth* *Vpc=0.62 p.u.*	*30% of depth* *Vwt=0.73 p.u.*
A 3-phase voltage dip with 20% of depth *Vpcc=0.8 p.u.*	*17% of depth* *Vpc=0.83 p.u.*	*13% of depth* *Vwt=0.86 p.u.*
A 3-phase voltage dip with 15% of depth *Vpcc=0.85 p.u.*	*13% of depth* *Vpc=0.87 p.u.*	*10% of depth* *Vwt=0.90 p.u.*

Table 7.5 Voltage module at different parts of the electric connection infrastructure for several voltage dips with key depths.



(a) (b)

(c)

Figure 7.29 Ireactive / Itotal ratio at the PCC, *(a)* during a 3-phase 50% voltage dip, *(b)* during a 3-phase 20% voltage dip and *(c)* during a 3-phase 15% voltage dip.

Based on the simulation results illustrated in Table 7.5, for voltage dips with less than the 20% of depth, the wind turbine does not inject reactive power because the voltage at the wind turbine terminals is up to 0.85p.u. Consequently, it is necessary to change the voltage limit to start injecting reactive current to fulfill the REE requirements.

Looking at the results shown on Table 7.5, for voltage dips with 15% of depth at the PCC, there is a 10% voltage dip at wind turbine terminals. So, to fulfill the REE grid code, the wind turbines have to start injecting reactive power with only a 10% voltage drop at their terminals.

As regards to the last voltage limit modification, the voltage limit to start injecting the maximum reactive current, based on Table 7.5, is elevated to 0.75p.u. In this way, the modified Ireactive / Itotal curve to fulfill the REE requirements at the PCC using wind turbines is depicted in Figure 7.30.

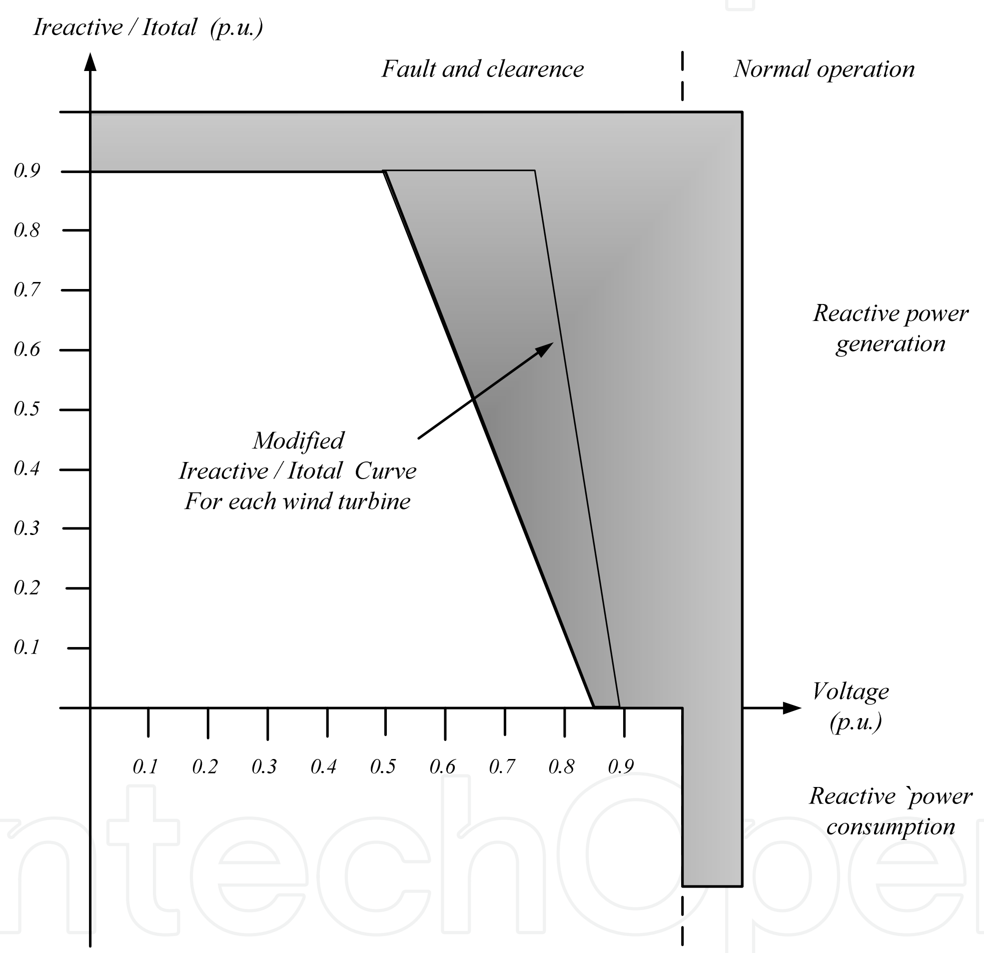
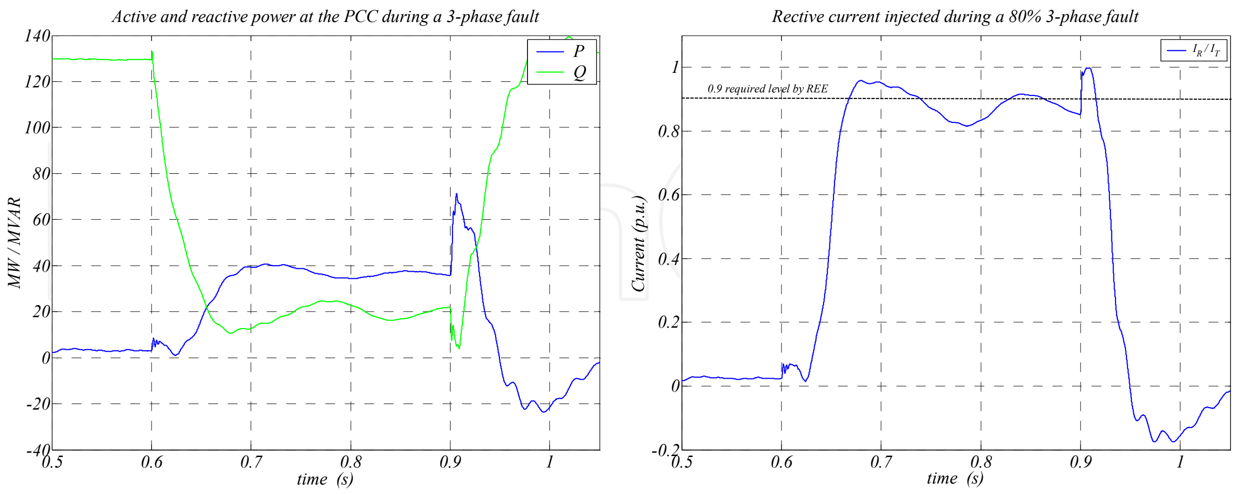


Figure 7.30 Modified Ireactive / Itotal curve depending on the voltage to fulfill the REE requirements at the PCC.

Even with this modification, the offshore wind farm does not fulfill the grid code requirements at the PCC, due to the fact that the transmission system generates inductive reactive power, see Table 7.4.

To verify this point, the same scenario of the section 7.4 with the same conditions (generating the 90% of the rated power) is simulated, but this time, the wind turbines have modified their Ireactive /Itotal curve (see Figure 7.30). The simulation results of the scenario shown in Figure 7.21 with modified Ireactive /Itotal curve are depicted at Figure 7.31.

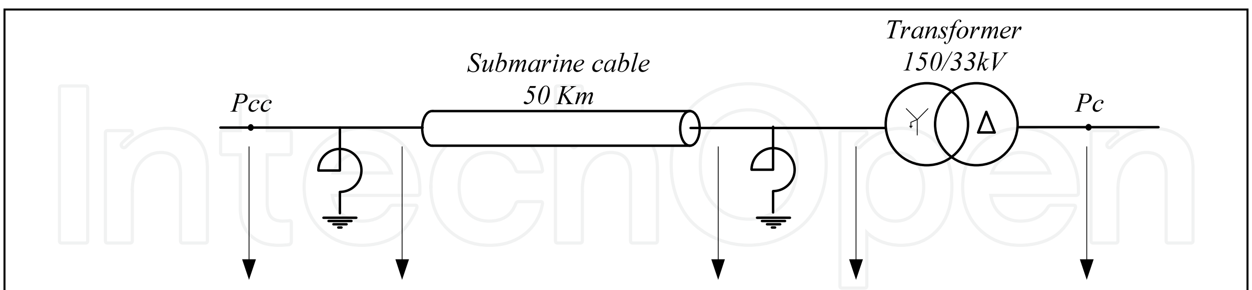


(a) (b)

Figure 7.31 Active and reactive power at the PCC *(a)* and Ireactive / Itotal at the PCC *(b)* for the considered offshore wind farm with modified Ireactive / Itotal curve.

As can be seen from the results displayed on Figure 7.31, even with the modified Ireactive / Itotal curve, the wind farm does not fulfill the REE grid code requirements. The reason for not fulfill code requirements is the inductive reactive power generated in the transmission system. At the PC the wind farm injects the proper quantity of capacitive reactive power, but at the PCC does not (Table 7.6)

To solve this problem, one possibility is to increase the size of the DC chopper. In this way, the DC chopper can be able to consume more active power and the wind turbines will inject less active power and more capacitive reactive power.



During the voltage dip (with modified Ireactive /Itotal curve)					
P	*24 MW*	*24 MW*	*26 MW*	*26.5 MW*	*28 MW*
Q	*32 MVAR (c)*	*34 MVAR (c)*	*35.5 MVAR (c)*	*38 MVAR (c)*	*57 MVAR (c)*

Table 7.6 Active and reactive power at all the points of the transmission system during a 80% 3-phase voltage dip (With modified Ireactive / Itotal curve), (i) inductive reactive power and (c) capacitive reactive power.

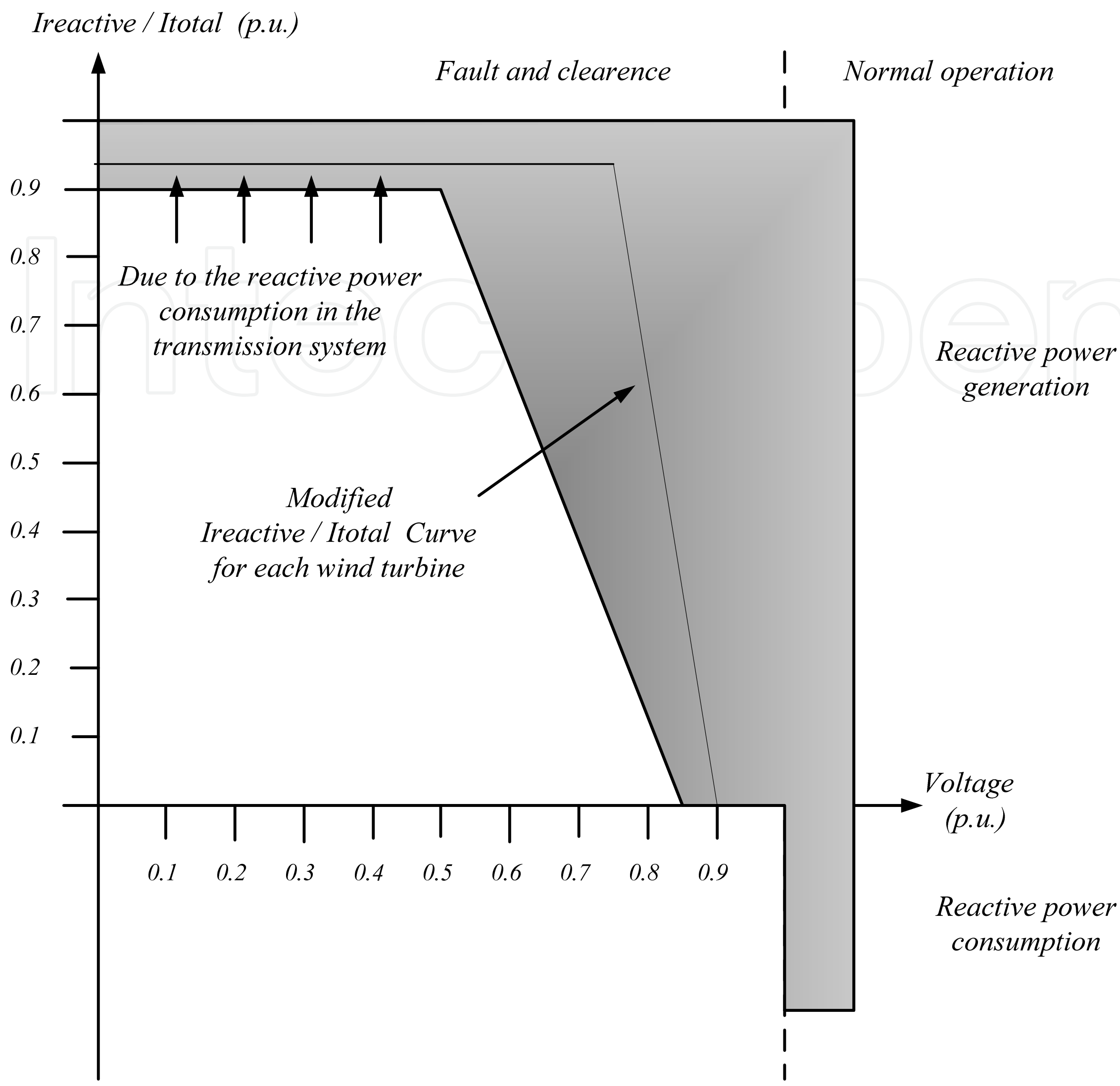


Figure 7.32 Modified Ireactive / Itotal curve depending on the voltage to fulfill the REE requirements at the PCC by reducing the injected active power during faults.

7.5.2 Characterization of auxiliary equipment, STATCOM

Another option is the use of a STATCOM [128] at the PCC as an auxiliary system. The wind turbines of the offshore wind farm can inject the main amount of the reactive power and reduce the generated active power during a voltage dip at the PCC (Figure 7.30), then, at the PCC the auxiliary equipment can inject the rest of the capacitive reactive power. This STATCOM also can provide some other services like: power factor control.

Moreover, using a STATCOM at the PCC, it can provide the required capacitive reactive power for voltage dips with less than the 20% of depth. This means that the voltage limit of the wind turbines to start injecting reactive power can remain at V=0.85 p.u. without increments (Figure 7.33). As a result, for any voltage reduction at the inter turbine grid, for example of the 10 % (not caused by a voltage reduction at the PCC), the wind turbines will not prioritize the injection of reactive current.

Focusing on the STATCOM, if there is considered that Ireactive / Itotal curve is only modified in voltage (only voltage limits adjusted, Figure 7.30), the STATCOM has to compensate the inductive-reactive power generated at the transmission system during voltage dips. This means that the rated power of the STATCOM depends on the inductive component of the submarine cable and the leakage inductance of the step-up transformer.

Therefore, the less are this inductive components, the less is the generated inductive reactive power at the transmission system and the less is the necessary rated power of the STATCOM to fulfill the grid codes.

An option to reduce the needed reactive power at the PCC during voltage dips is to provide thyristors to the onshore static compensation, giving them the ability to disconnect themselves when a fault occurs. The other way is the reduction as far as possible the leakage inductance of the step-up transformer at the offshore platform.

In short, the size of the STATCOM depends on the inductive reactive energy generated in the transmission system during the voltage dip and the amount of the active / reactive power injected by wind turbines, i.e. the modification of the Ireactive / Iactive curve of the wind turbines by increasing their injected reactive current. Therefore, many options to inject the proper reactive power at the PCC are allowed.

However, due to the huge amount of inductive reactive power generated in the transmission system, 25 MVAR in the worst case (80% symmetric voltage dip, 20% of residuary voltage), Table 7.4. The use of a STATCOM to compensate the reactive power generated in the transmission system will require a 125 MVAR rated power.

Consequently, the proposed solution priorities the use of the grid side converters of the wind turbines to reduce active power and inject the biggest part of the required reactive power.

Considering the voltage dip propagation through the transmission system of the considered scenario, for voltage dips with less depth than 20%, the voltage at the wind turbine terminals is up to 0.85p.u. Therefore, to keep the voltage limit of the wind turbines to start injecting reactive power at 0.85 p.u., the STATCOM has to provide the required reactive power for voltage dips with less depth than 20%

The Ireactive / Itotal requirement at the PCC for a voltage dip with 20% of depth (Appendix C: REE Grid Code Requirements for Voltage Dips) is 0.128. Consequently, for the worst case, when the wind farm is generating the rated active power (injecting the rated active current) the required reactive current is 0.13 p.u., equations (147) - (149).

$$I_{reactive} / I_{total} = \frac{I_{reactive}}{\sqrt{I_{reactive}{}^2 + I_{active}{}^2}} \tag{147}$$

$$I_{reactive} / I_{total} = 0.128 = \frac{I_{reactive}}{\sqrt{I_{reactive}{}^2 + 1^2}} \tag{148}$$

$$I_{reactive} = \sqrt{\frac{0.128^2}{1-0.128^2}} = 0.13 \tag{149}$$

In this way, by using a STATCOM of 20 MVAR (0.13 p.u.) rated power at the PCC, the change of the minimum voltage limit of the wind turbines to prioritize the reactive power injection is not necessary.

The model and characteristics of the considered STATCOM used to verify the proposed electric connection infrastructure are summarized in Appendix G: Considered STATCOM Model to Validate the Proposed Solution.

7.5.3 Proposed solution

For the proposed solution, a 20 MVAR STATCOM (13%) and the modification of the Ireactive / Itotal curve depending on the voltage shown at Figure 7.33 is considered.

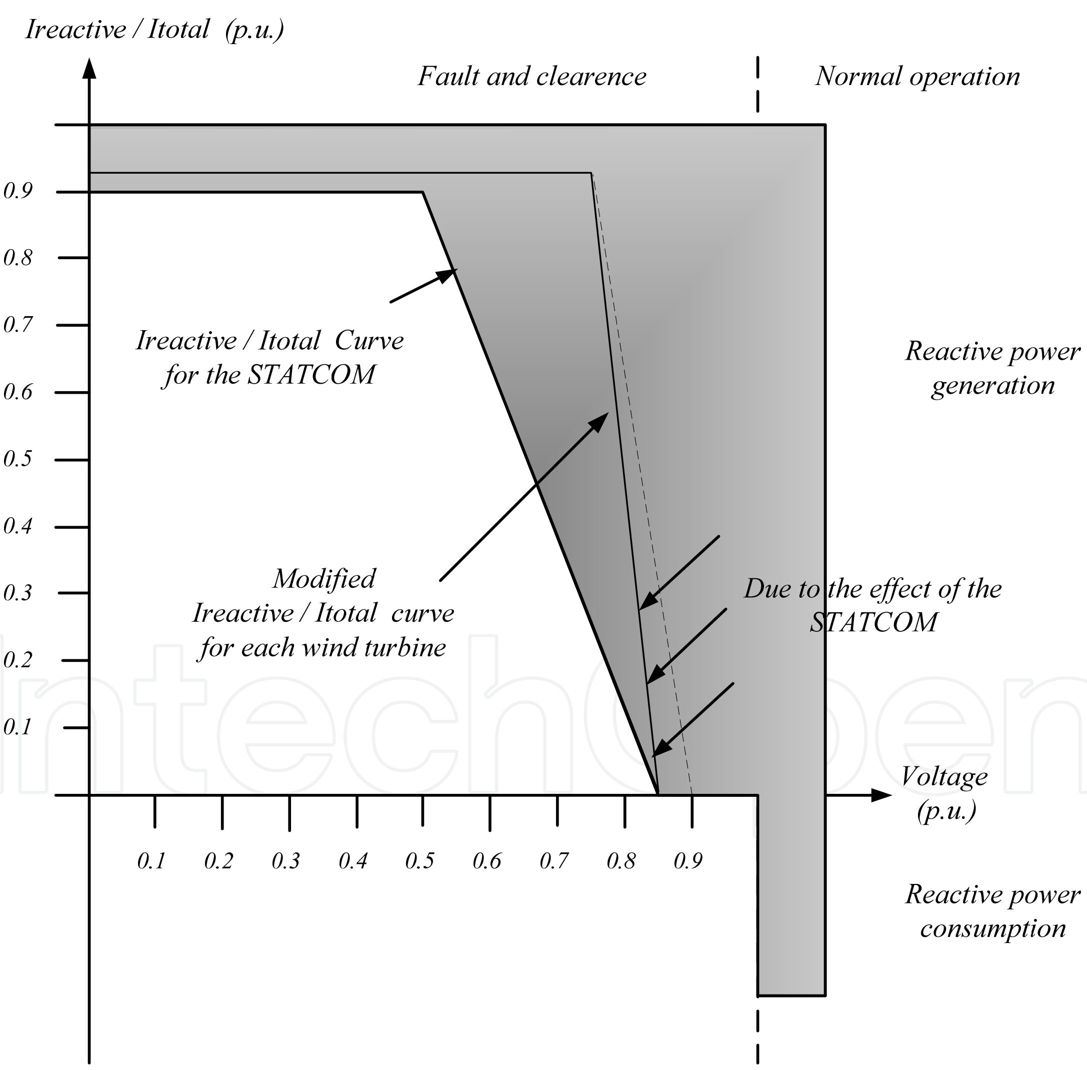


Figure 7.33 Proposed Ireactive / Itotal curve depending on the voltage to fulfill the REE requirements at the PCC.

Therefore, in the proposed solution, the compensation of the inductive reactive power generated in the transmission system is made by grid side converters of the wind turbines. Consequently, the performed Ireactive / Itotal curve modification, the increment in the Ireactive / Itotal relation depends on the inductive reactive power generated in the transmission system.

Thus, in order to keep the Ireactive / Itotal relation as low as possible, there is considered that the onshore compensation can be disconnected during voltage dips at the PCC, reducing in 2 MVARs the required reactive power at PCC. As a result, for the new curve the maximum Ireactive / Itotal relation is modified from 0.9 to 0.93.

Nevertheless, for the purposed complete scheme, besides the STATCOM and onshore variable inductive compensations, all the proposed solutions for the problems discussed in previous sections are taken into account: The fixed inductive reactive compensators at both ends of the submarine cable adjusted for the case when the wind farm is transmitting the rated power (32 MVAR + 32 MVAR for 50 Km of the selected cable) and the passive filters for the main resonance of the system (330 Hz).

The transient over voltages and over currents do not affect to the transmission system elements such as the step-up transformer or the submarine cable. Nevertheless, the more delicate devices (power electronic converters) need to be protected. Thus, for the considered scenario is considered that the wind turbines and the STATCOM are provided with those devices.

Therefore, depending on those protection devices, the passive filters evaluated in section 7.3.3.1 to improve the transient response of the system may be not required. However, these passive filters are considered for the proposed solution.

In short, the complete electric scheme of the purposed AC offshore wind farm is depicted in Figure 7.34.

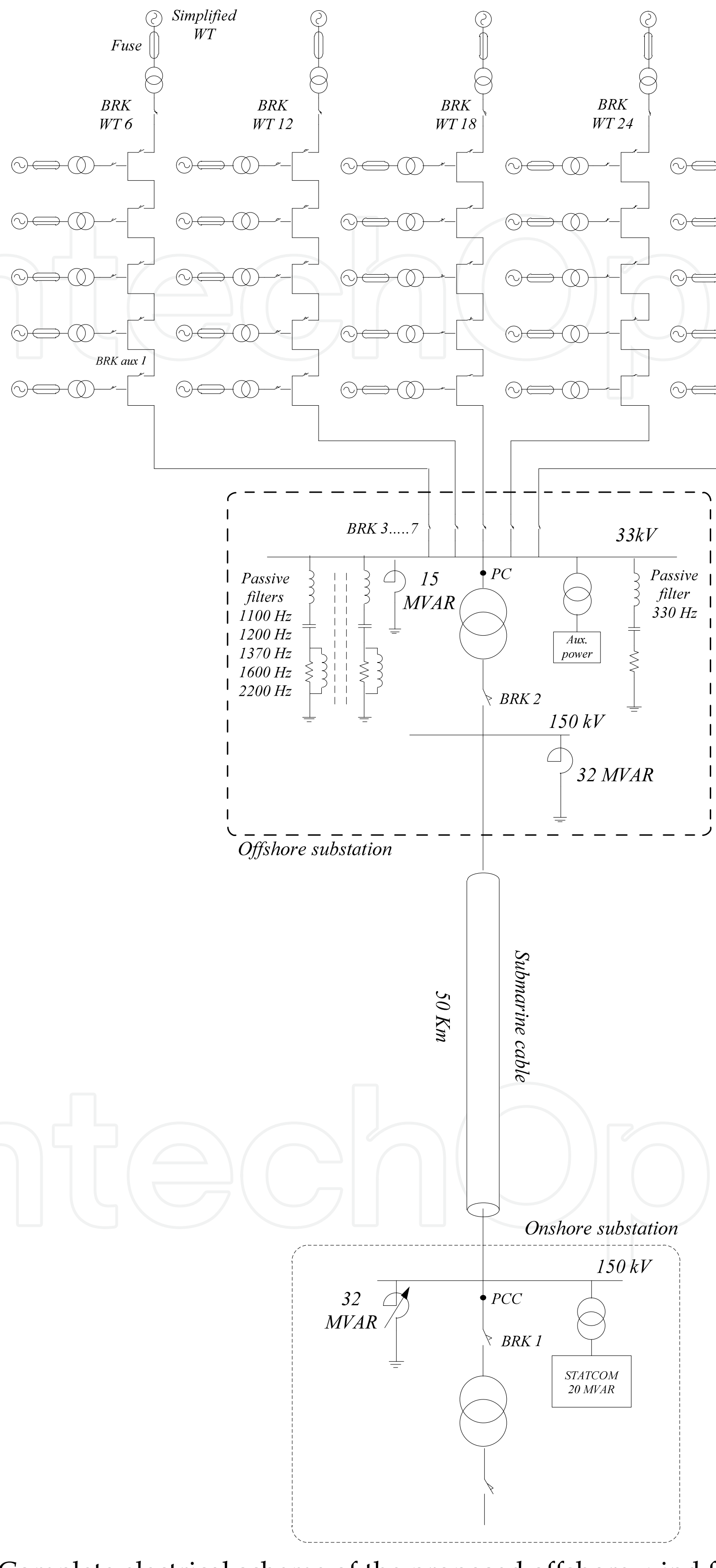


Figure 7.34 Complete electrical scheme of the proposed offshore wind farm.

7.5.4 Verification via PVVC of the purposed wind farm

For testing and validation of wind turbines, REE has defined a procedure detailing all the tests and characteristic in the validation process, the PVVC (Procedimiento de verificación, validación y certificación de los requisitos del PO 12.3 sobre la respuesta de las instalaciones eólicas ante huecos de tensión) [101]. Therefore, as is made in section 5.2.2.4 for wind turbines, in the present section, this procedure with the same conditions is applied to the entire offshore wind farm.

Thus, upon the proposed wind farm, the four faults defined in the PVVC are applied (Table 5.12). Then, the voltage and current is measure at the PCC to analyze if the proposed wind farm accomplishes with the REE requirements.

Results of a fault category 1: Three-phase fault - partial load

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during a period of 150ms after the beginning of the fault:	-0.1500	0
Net reactive power consumption, during a period of 150ms after the clearance of the fault:	-0.0900	0
Net reactive current consumption, in cycles of 20ms, during a period of 150ms after the clearance of the fault:	-1.5000	0
Net active power consumption during the fault:	-0.1000	0
Net reactive power consumption during the fault:	-0.0500	0
Fulfillment of the $I_{reactive} / I_{total}$ requirement:	0.9000	0.9367

Table 7.7 Summarized results of a 1st category fault for the test defined in the PVVC.

Results of a fault category 2: Three-phase fault - full load.

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during a period of 150ms after the beginning of the fault:	-0.1500	0
Net reactive power consumption, during a period of 150ms after the clearance of the fault:	-0.0900	0
Net reactive current consumption, in cycles of 20ms, during a period of 150ms after the clearance of the fault:	-1.5000	0
Net active power consumption during the fault:	-0.1000	0
Net reactive power consumption during the fault:	-0.0500	0
Fulfillment of the $I_{reactive} / I_{total}$ requirement:	0.9000	0.9164

Table 7.8 Summarized results of a 2nd category fault for the test defined in the PVVC.

Graphic results:

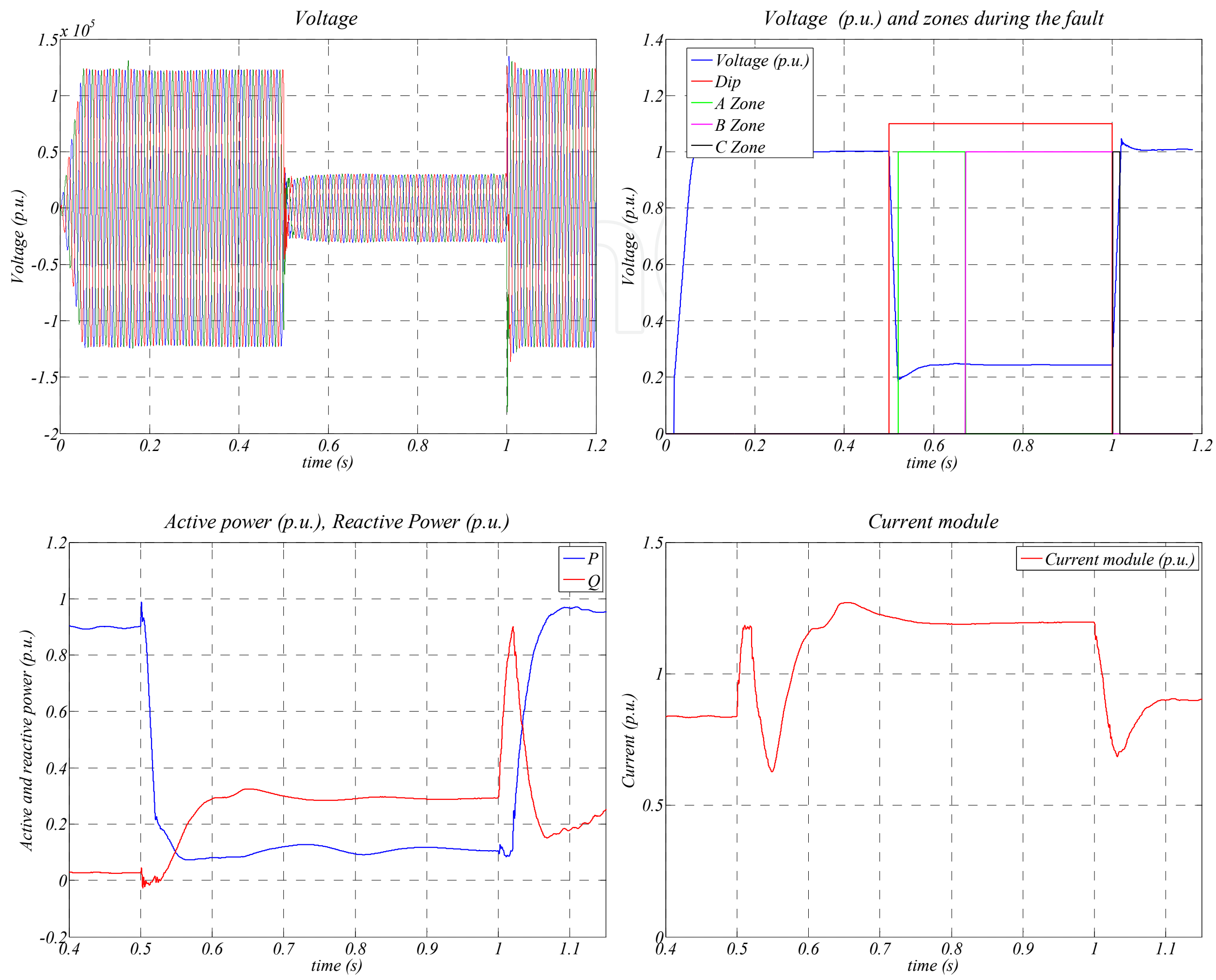
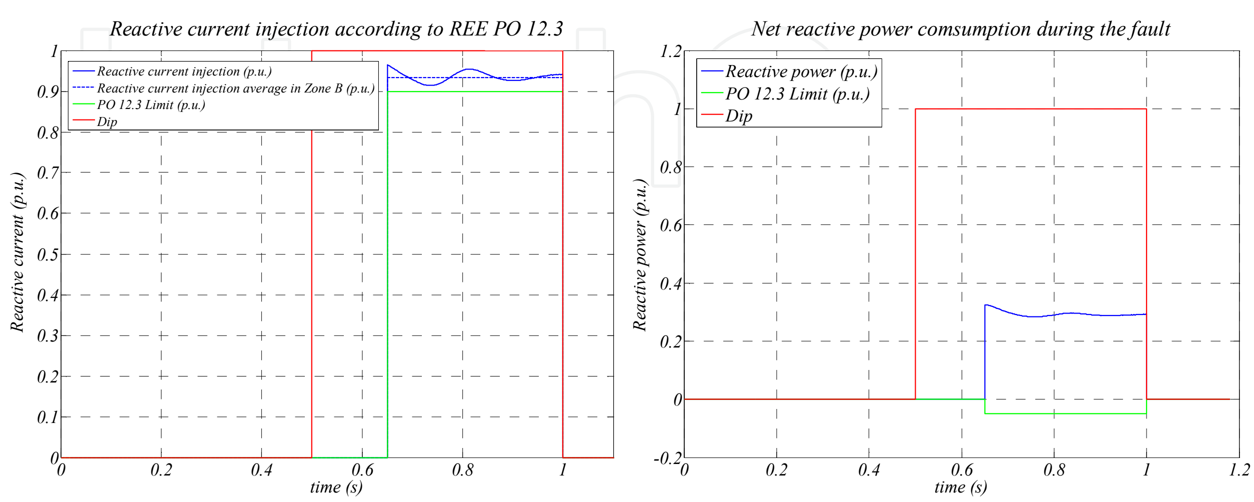


Figure 7.35 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, voltage (module and signals), power and current results.



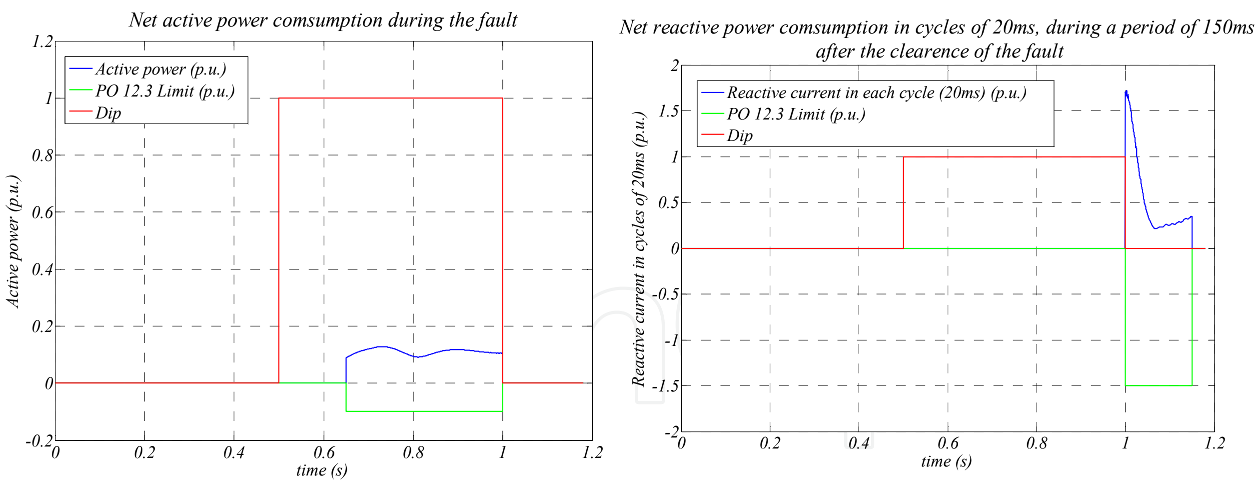


Figure 7.36 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, reactive current and power consumption in B zone and reactive current consumption in C zone.

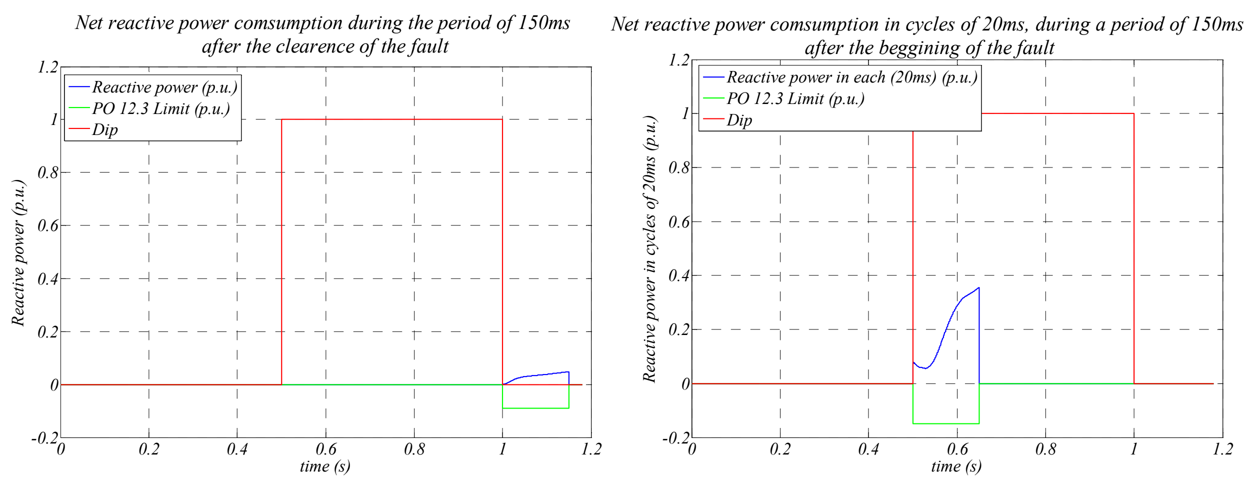


Figure 7.37 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, reactive power consumption in C zone and A zone.

<u>Results of a fault category 3: Two phase ungrounded fault - partial load</u>

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.4000	0
Net reactive power consumption, during the maintenance of the fault:	-0.0400	0
Net active power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.3000	0
Net active power consumption, during the maintenance of the fault:	-0.0450	0

Table 7.8. Summarized results of a 3rd category fault for the test defined in the PVVC.

Results of a fault category 4: Two phase ungrounded fault - full load

	Limit P.O. 12.3	Test results
Net reactive power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.4000	0
Net reactive power consumption, during the maintenance of the fault:	-0.0400	0
Net active power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.3000	0
Net active power consumption, during the maintenance of the fault:	-0.0450	0

Table 7.9 Summarized results of a 4th category fault for the test defined in the PVVC.

Graphic results:

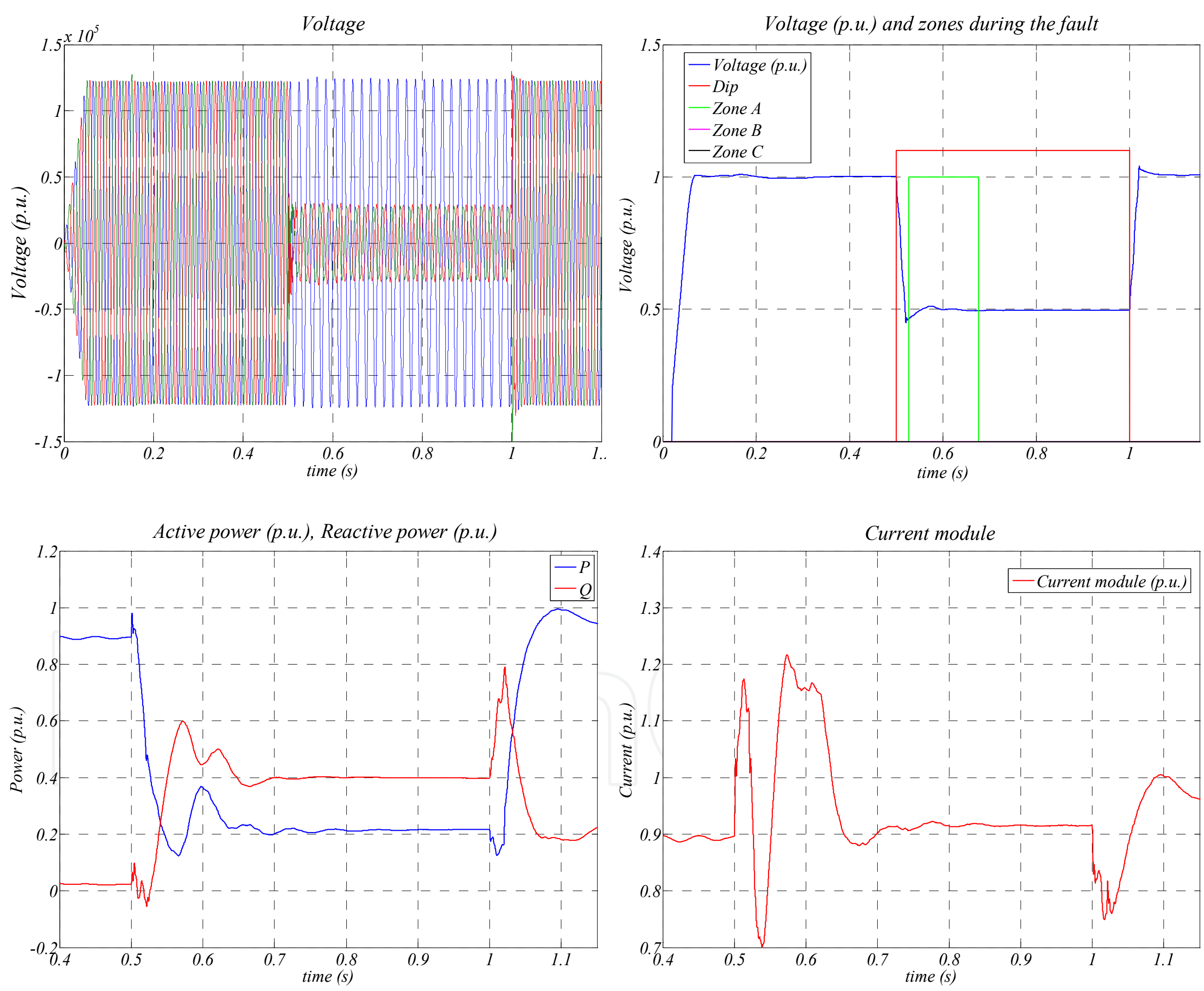


Figure 7.38 Summarized graphical results of a 4th category fault for the test defined in the PVVC, voltage (module and signals), power and current results..

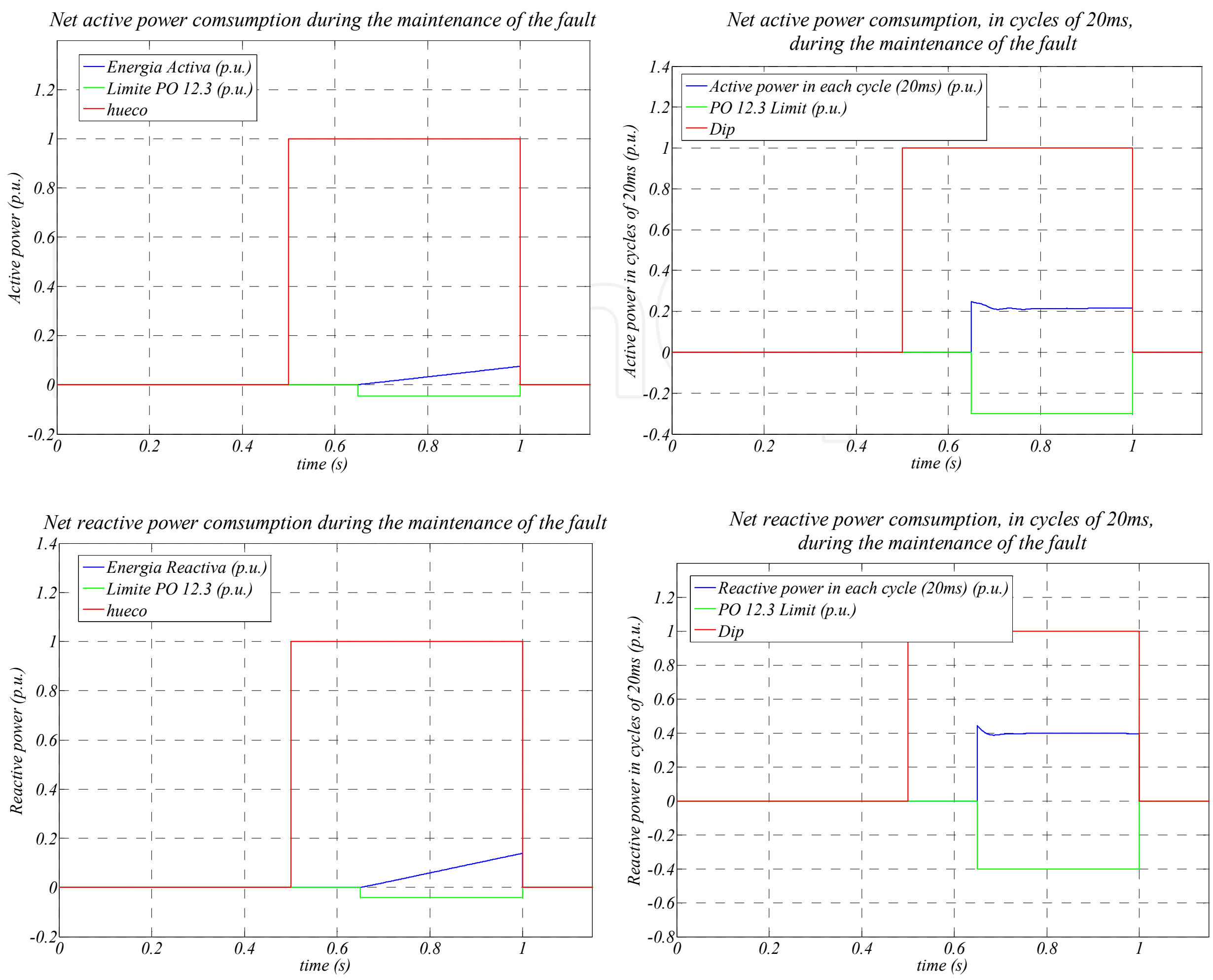


Figure 7.39 Summarized graphical results of a 4th category fault for the test defined in the PVVC, active and reactive power consumption in B zone.

As can be seen from Figure 7.35 - Figure 7.39, the proposed wind farm fulfills the reactive power and the fast recovery (to the pre-fault values) requirements of the REE grid code. Therefore, the proposed offshore wind farm is suitable to connect to a distribution grid operated by REE.

7.6 Chapter conclusions

The electric connection infrastructure of the offshore wind farm is composed by several inductive and capacitive elements. Due to this fact, the energizing of the circuit and the transient responses are especially of concern.

The analysis performed in the present chapter reveals that a fault clearance (by the circuit breaker) in a feeder of the inter-turbine grid can damage the power electronic devices connected to this grid. The short circuit current interruption causes an over-voltage of 50% in the collector point.

Besides, the faults or voltage dips at the PCC which provokes the de-energizing and energizing of the submarine cable also causes transient over-voltages. Therefore, all the power electronic devices connected to the electric connection infrastructure of the offshore wind farm must be provided with the proper protective devices (surge arresters, etc…) to ride through those transient over-voltages.

In the same way, some studies give description of the phenomenon that produces high over voltages internally in the transformer winding caused by high frequency transients [121], which apparently are responsible for the transformer insulation failures. Thus, also the transformers have to be provided with the proper protective devices.

The use of passive filters to minimize the voltage peaks and the high frequency components of the transients can be an option. But, as is mentioned before, the passive filters definition is based on the perfect knowledge of parameters. Therefore, in real conditions, where the parameters are not well known, passive solutions might not be suitable.

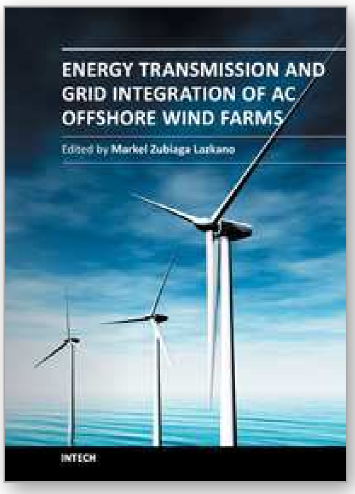
Another point evaluated in this chapter is the behavior of the offshore wind farm upon voltage dips at the PCC, from the point of view of the REE grid code requirements. To connect an offshore wind farm to the distribution grid has to fulfill the rules established by the system operator. One important requirement is the reactive power injection to the main grid during voltage dips at the PCC.

To achieve this requirement is important to know the behavior of the submarine cable, because this element can generate inductive reactive power or capacitive reactive power depending on the applied voltage and the current through the cable.

Due to this fact, depending on the submarine cable characteristics, the cable and its reactive power compensators (see chapter 4, section 4.3) both of them can generate inductive reactive power during a voltage dip, making harder to fulfill the grid code requirements.

Nevertheless, full-converter wind turbines and their capability to inject reactive current can help to fulfill the reactive current requirement at the PCC generating the biggest part of the required reactive current.

As a result, using full-converter wind turbines and an STATCOM as auxiliary equipment at the PCC is possible to fulfill the REE grid code requirements, as can be conclude from the results of the section 7.5.4.



Energy Transmission and Grid Integration of AC Offshore Wind Farms
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This book analyses the key issues of the offshore wind farm's energy transmission and grid integration infrastructure. But, for this purpose, there are not evaluated all the electric configurations. In the present book is deeply evaluated a representative case. This representative case is built starting from three generic characteristics of an offshore wind farm: the rated power, the distance to shore and the average wind speed of the location. Thus, after a brief description of concepts related to wind power and several subsea cable modeling options, an offshore wind farm is modeled and its parameters defined to use as a base case. Upon this base case, several analyses of the key aspects of the connection infrastructure are performed. The first aspect to analyze is the management of the reactive power flowing through the submarine cable. Then, the undesired harmonic amplifications in the offshore wind farms due to the resonances and after this, transient over-voltage problems in the electric infrastructure are characterized. Finally, an offshore wind farm connection infrastructure is proposed in order to achieve the grid code requirements for a specific system operator, but not as a close solution, as a result of a methodology based on analyses and simulations to define the most suitable layout depending on the size and location of each offshore wind farm.